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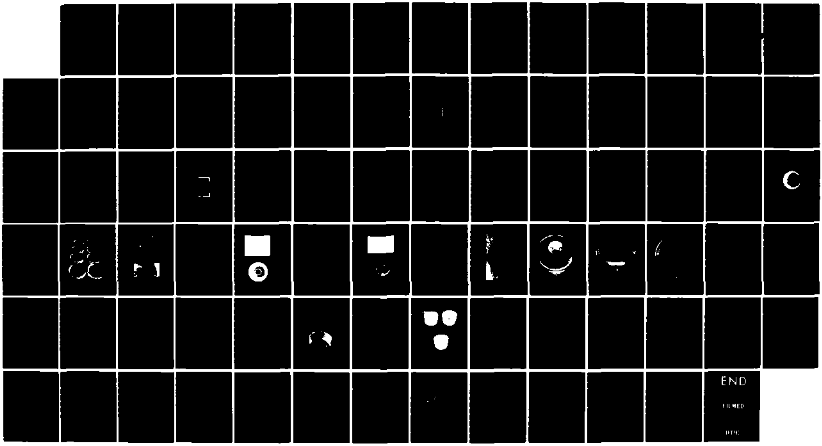

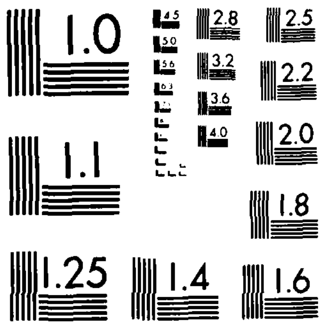

MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS 1963 A

Contract No. DAAH01-76-C-1103
Report No. IITRI-B6142-23

A MANUFACTURING METHODS AND TECHNOLOGY PROGRAM--PRODUCTION METHODS FOR SQUEEZE CASTINGS

U.S. Army Missile Command
Redstone Arsenal, Alabama 35809

Attention: Mr. John Melonas,
DRSMI-RLM

Prepared by

M. Virani, S. Rajagopal, and S. Storchheim

IIT Research Institute
10 West 35 Street
Chicago, Illinois 60616

Interim Report for the Period
1 July 1976 to 31 May 1978

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FOREWORD

This Interim Report covers the work performed under Contract No. DAAH01-76-C-1103 from 1 July 1976 to 31 May 1978. The report is designated internally as IITRI-B6142-23. This contract with IIT Research Institute was under the technical supervision of Mr. John Melonas and Mr. James Wright of the U.S. Army Missile Command, Redstone Arsenal.

Mr. S. Storchheim, Manager of Metalworking and Foundry Technology, was the principal investigator during the final eight months of the project, taking over from Dr. K. M. Kulkarni. Substantial contributions were also made by M. Virani, Research Metallurgist; S. Rajagopal, Associate Metallurgist; Y. Lee, Assistant Metallurgist; J. Dorcic, Technical Assistant; J. Katos, Experimentalist; M. Dimenn, Assistant Experimentalist; and D. Wells, Technician. The report was typed by Mrs. M. Dineen and edited by Ms. V. Johnson.

S. Storchheim
Manager, Metalworking
and Foundry Technology

M. A. H. Howes, Director
Metals Research

ABSTRACT

A MANUFACTURING METHODS AND TECHNOLOGY PROGRAM--
PRODUCTION METHODS FOR SQUEEZE CASTINGS

Squeeze casting is a hybrid of conventional casting and forging techniques and possesses many of the advantages of both techniques. This project was aimed at developing the squeeze casting process to achieve cost reductions in the manufacture of missile components. Two PATRIOT missile components were investigated--the forward dome and the case preform. Both components were squeeze cast from D6AC steel.

This study served to extend the squeeze casting technology to include large, ferrous castings. Process development was achieved successfully for the forward dome as well as the case preform. In both cases, defect-free castings (as judged by radiography) were obtained, and these possessed as-squeeze cast surfaces that were superior to the surfaces resulting from conventional sand casting or hot forging. It is expected that the squeeze casting process will show significant cost savings over conventional processing techniques for these missile parts.

Letter on file

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A MANUFACTURING METHODS AND TECHNOLOGY PROGRAM--
PRODUCTION METHODS FOR SQUEEZE CASTINGS

1. INTRODUCTION

The objective of this project was to develop manufacturing methods necessary to reduce the high machining cost associated with high-strength castings and forgings currently used in Army missile systems. The project aimed at developing the squeeze casting process for the purpose of (1) lowering the cost of the castings with minimum subsequent machining requirements, (2) casting preforms to replace more costly forged preforms for subsequent shear spinning, and (3) developing the process for a faster production rate of the cast and shear-spun missile components. The components investigated were the PATRIOT forward dome (sketch 111775) and case preform (sketch 111075), both made from D6AC steel. top 111

IIT Research Institute has conducted much research on squeeze casting or liquid metal forging. Basically, this process consists of metering molten metal into a bottom die cavity, allowing it to cool below the liquidus, then applying pressure by means of a top punch and allowing the solidification to go to completion under high pressure. As the name suggests, it is a process intermediate between conventional casting and forging and combines the advantages of both. Thus, it can be used for making parts of greater complexity than forgings and of better product quality than castings. Further, the amount of finish machining can be reduced compared to both the conventional forging and casting methods.

It is anticipated that, under production conditions, both the components will show substantial reduction in cost when machined from squeeze castings as against the current technique of machining them from forged stock or castings. Other factors contributing to reduction in cost will be higher material yield, consequent substantial reduction in the degree of required finish machining, and lower rejection rate of the squeeze castings.

During the course of this program, process parameters such as melt pouring temperature, die temperature, press tonnage, and duration of pressure application were studied with reference to the resultant casting quality. Optimum parameters were found that minimized or eliminated casting defects, resulting in defect-free, acceptable squeeze castings. This led to the successful production of deliverable items of both components and the establishment of process specifications for each component.

This report summarizes the work conducted throughout the project. First, the principle of the process and its advantages are described and some published work is reviewed. Then, the geometry of the two components is discussed along with the considerations of design and fabrication of the tooling. Equipment and procedural details concerned with the hydraulic press, melting and melt transfer, die heating and coating, and experimental procedure are presented briefly. The squeeze casting trials for the two components are reviewed along with the influence they had on various tooling modifications that became necessary. The squeeze castings were then evaluated in terms of surface conditions, internal structure, and mechanical properties. Factors such as part geometry and various process variables and die materials are considered, and generalizations are made as to how the applicability of the process can be considered or determined for any particular component. Preliminary process specifications are drawn for the two components, and a summary of the main accomplishments are presented.

2. TECHNICAL DISCUSSION

2.1 Squeeze Casting--Process Parameters and Advantages

The process is variously termed liquid metal forging, squeeze casting, or extrusion casting. It is essentially a hybrid of the forging and the casting processes. Much work has been conducted on the process, both in terms of research and commercial applications, in Russia for quite some time although it is a relative newcomer in the United States. There are various publications discussing the major facets pertaining to the technique.[1-7]

The four stages of squeeze casting are shown in Fig. 1. They consist of metering the molten metal into the die cavity, allowing it to solidify partially, applying pressure to fill the die cavity and to accomplish solidification under pressure, and, finally, removing the completed casting from the die cavity. Initially, the molten metal is somewhat superheated, a certain time is allowed for the melt to cool in the die cavity, and during this period partial solidification takes place. In the third stage, when the dies are closed, the pressure applied displaces the metal to fill the die cavity completely and the interdendritic porosity is eliminated by pressure feeding the molten metal. The pressure is maintained long enough to complete the solidification. The pressure level is high enough to eliminate all traces of shrinkage porosity and to keep any gas in solution so that the casting is completely free of porosity.

It is important to distinguish the squeeze casting process from the ferrous die casting process.[8,9] As the name suggests, the latter is essentially a die casting process in which the molten metal is forced under great pressure into the die cavities through narrow runners and gates. Although the injection pressure is high, the metal usually solidifies first at the narrow entrances to the die cavities and the metal in the die

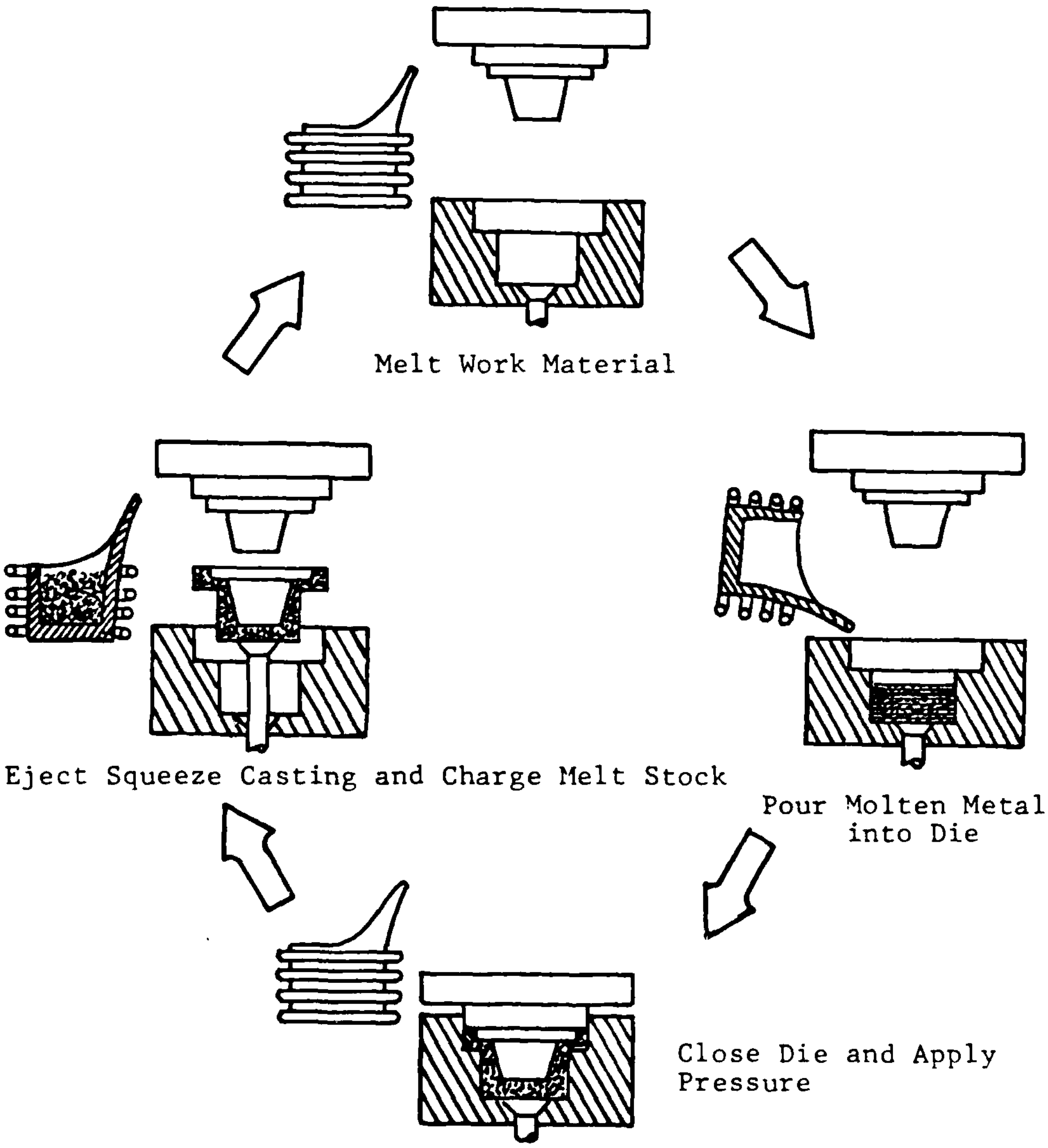


Figure 1

Production Sequence for Squeeze Casting

Table 1 (cont.)

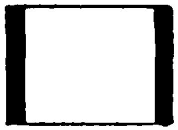
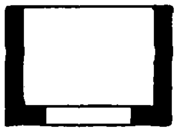
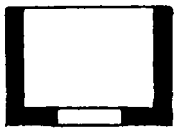
Casting Design No. and Shape[a]	Wt. of Squeeze Casting, lb	Yield,[b] %	Advantages	Disadvantages
4 	175	47	1. Simple die, punch, and ejection system design. 2. Simple system for pouring liquid metal will be required. 3. Because of large volume, more time will be allowable for melt transfer and load application.	1. Poor yield. 2. Because of large plan area (211 $in.^2$), the maximum pressure is limited to 9500 psi which may be inadequate. 3. Stripper plate must be removed to eject casting.

[a]See corresponding die designs in Fig. 4.

[b]Based on estimated machined weight of 82 lb and as-cast weights.

Table 1

ALTERNATIVE CASTING AND DIE DESIGNS FOR CASE PREFORM

Casting Design No. and Shape[a]	Wt. of Squeeze Casting, lb	Yield,[b] %	Advantages	Disadvantages
1 	109	75	1. Maximum yield. 2. Minimum requirement for finish machining. 3. Highest capability for unit squeeze casting pressure.	1. The melt comes in immediate contact with a large area of the die and may freeze rapidly. Hence, will require special melt transfer. 2. The stripping force requirement will be very large. 3. High risk of poor product quality because of items 1 and 2.
2 	136	60	1. High material yield. 2. Simple system can be used for melt transfer and more time will be allowable for melt transfer and load application. 3. Pressure of up to 20,000 psi can be applied.	1. Casting may stick badly on the punch and may also crack while cooling.
3 	147	56	1. Simple system can be used for melt transfer and more time will be allowable for melt transfer and load application. 2. Pressure of up to 20,000 psi can be applied. 3. The stripper plate will force the casting to remain in lower die which can then be ejected easily. 4. Good material yield.	1. Ejection of the casting will require removal of the stripper plate.

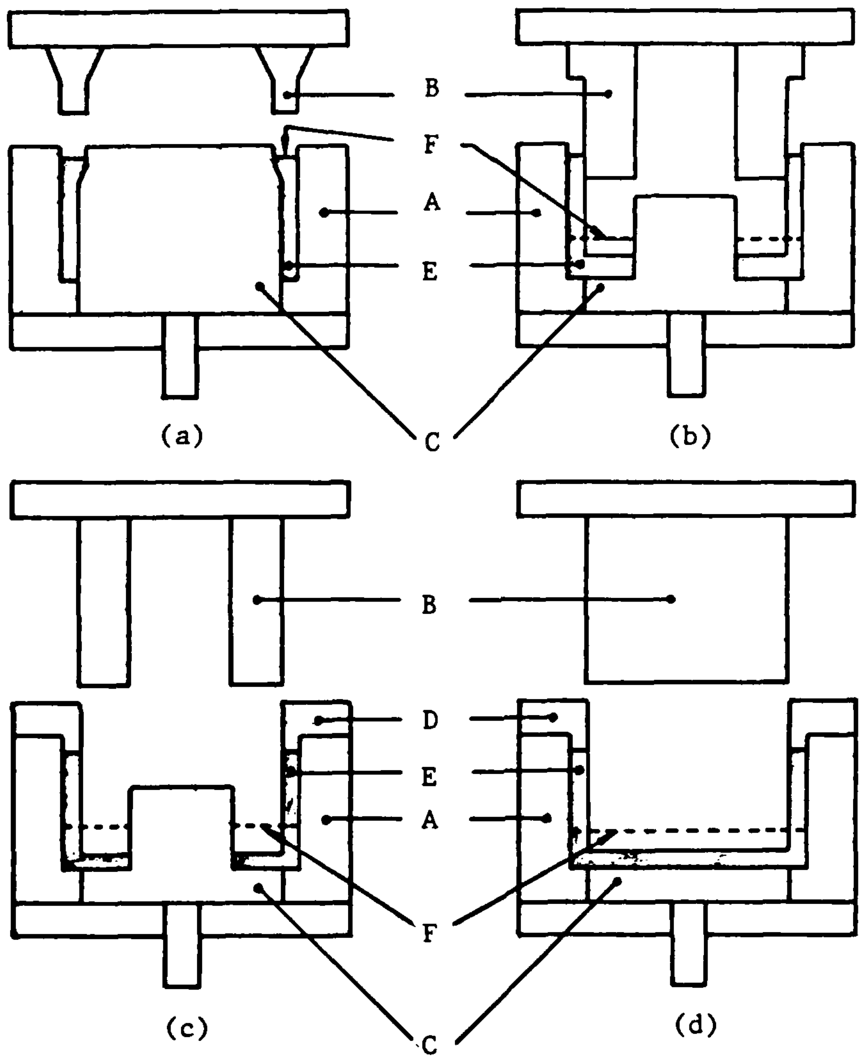


Figure 4

Four Alternative Die Designs for Preform

A - Lower Die
B - Punch
C - Ejection Pin
D - Stripper Sleeve
E - Squeeze Casting
F - Melt Level Prior to Die Closure

spun missile case is then heat treated and electron beam welded for the assembly. The portion of the spun preform that is welded is subjected to only two passes. The main requirements for the preform squeeze casting to be satisfactory for the end application are that it should be capable of being shear spun and it should respond well to EB welding.

Several alternative target designs were considered to produce the preform as a squeeze casting. Four of the designs that deserved closer attention are described below. The corresponding die designs are shown in Fig. 4, and the main advantages and disadvantages of each are summarized in Table 1.

For a high material utilization, it would be best to squeeze cast this component as an open-ended cylinder (Fig. 4a) with only a slight increase in wall thickness in one direction. However, the dies for making such a component would require the melt to be poured into a narrow gap corresponding to the thickness of the tubular part, and the melt would solidify extremely rapidly because of the relative thinness of the walls. This would make it very difficult to close the dies and apply pressure prior to completion of the solidification--at least in some portions of the thin-walled tube--and this could contribute to poor product quality. Moreover, in practice, it may be very difficult to guide the melt into the narrow gap corresponding to the wall thickness of the tube.

Another approach considered was to make the outside of the tube in the lower die and make the inside with an upper die. With this type of approach (Figs. 4b and c), the melt is introduced into the lower die and forms a relatively thick pool. It is only after the dies are closed and the top die displaces the melt that the thin-walled tubular part is formed, and such an approach is likely to have a much greater chance of success. With this approach, at least a partial closure must be allowed at one end so that the ram can apply pressure on this end face and feed melt into the tubular section to improve its quality.

The vertical side walls of the lower die near the skirt region, offset by the convex nature of the punch, made it equally likely that the squeeze casting might be retained by the lower die or by the punch. Consequently, ejection systems were provided in the lower die (ejection pin coupled to a hydraulic cylinder) as well as in the punch. The latter was provided with a mechanical linkage with chains to strip the casting off the punch using the press retraction force.

The main components of the die system, including all members that are subjected to high surface temperatures due to contact with the melt, were made from H13 chrome-molybdenum hot work die steel. This choice was based on the satisfactory performance of the material in past squeeze casting programs at IITRI. This is a commonly available, standard die steel possessing good thermal shock and medium-temperature strength properties.

The fabrication of the main die components was completed at the end of April, 1977. These components were subjected to surface oxidation by heating in air to 600°F. This treatment was intended to inhibit welding of the freshly machined surface to the melt during the initial experimental runs.

3.2 Case Preform

The case preform is a tubular part with approximately 17 in. diameter and 10 in. length, and the machined weight of the component is estimated to be 82 lb. Currently, two preforms are required per missile motor case. It is important for the preforms to have good response to heat treatment. The as-received hardness should be uniform and in the range of R_C 20-24. The desired grain size is 5 or smaller. The dimensional stability must also be good. In the spinning operation, starting from 0.524 in. wall thickness, two passes at ambient temperature are taken. The preform is then annealed, and a third pass is taken to bring the wall down to 0.077 in. in thickness, thus achieving a total reduction in thickness of about 86%. The

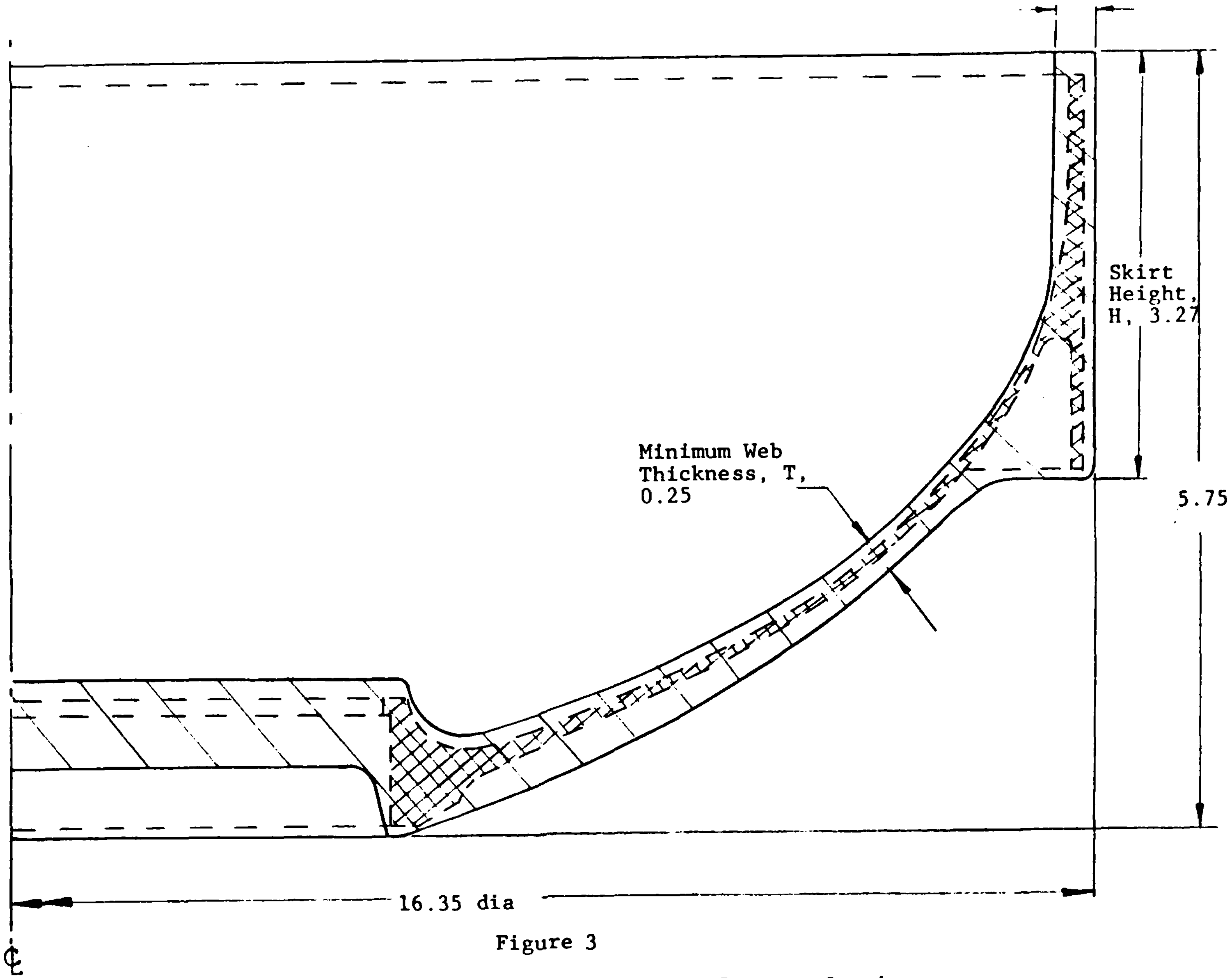


Figure 3

Revised Target Geometry for Forward Dome Squeeze Casting with Superimposed (dotted) Machined Part Outline

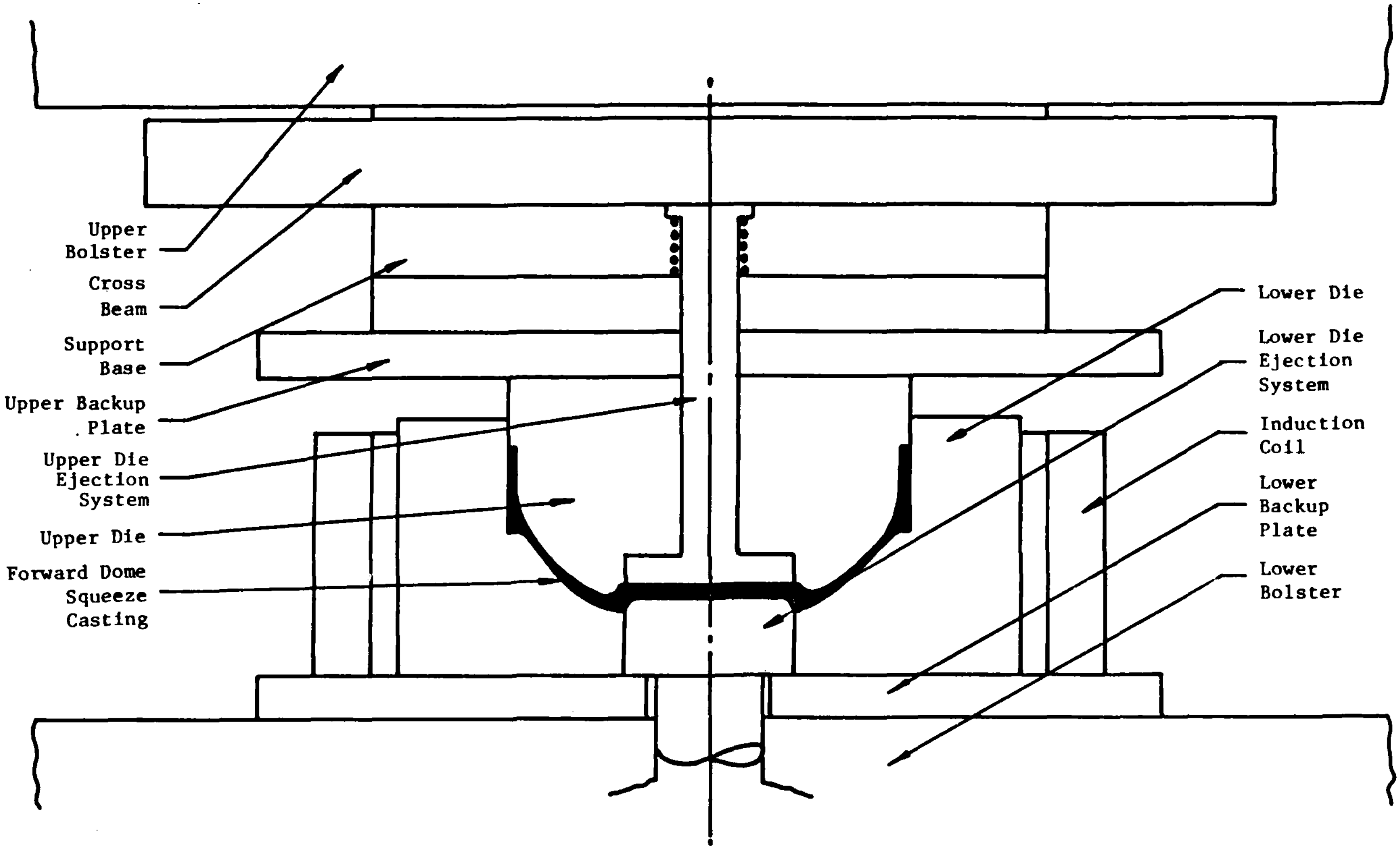


Figure 2

Schematic of Forward Dome Die Assembly

3. PART GEOMETRY AND TOOLING

This section describes the part geometry, target as a squeeze casting, and design and fabrication of the tooling for the forward dome and the case preform. The target geometry was selected as close to the finish-machined component as possible. Common die steels were chosen for all the tooling, except the backup members which were fabricated from hot-rolled steel.

3.1 Forward Dome

The PATRIOT forward dome is a bowl-shaped part 16 in. in diameter and nearly 6 in. in height, with a central hole, and a skirt on the periphery. In addition to its large area, the component is characterized by a thin wall of only 0.068 in. thickness over a large portion.

The geometry of this component suggested a relatively simple die design (Fig. 2) in which the outside surface of the dome is made by the lower die. The die has a concave inner detail, which can readily contain the molten work material transferred into it at the start of the squeeze casting cycle. The inside surface of the dome is made by the punch or the top die. Machining requirements on the forward dome squeeze casting include a marginal cleanup on the inside surfaces, draft removal near the skirt area, the entire outside surface of the dome, and the central hole.

The wall of the forward dome is very thin (only 0.068 in.), and it is unrealistic to attempt to cast this thin wall in a component of this size and shape. The dies were initially designed for a minimum casting thickness of approximately 0.25 in., resulting in a machining allowance of approximately 3/16 in. on the outside surface of the forward dome casting (Fig. 3). Incomplete die filling under these circumstances simply means that a greater volume of melt would be required, thereby increasing the machining allowance without any need for major die modifications.

that the die surface temperature increased as a function of superheat of the melt, initial die temperature, pressure, and mass of molten metal. Maximum surface temperatures for steel squeeze castings ranged from approximately 1500° to 1900°F. The zone of maximum heating only extended 0.080-0.100 in. below the surface.

The die surface temperature is also influenced by the mold coating,[18-20] and therefore the coating should have good heat insulating property. The mold coating acts as a separating agent and reduces any tendency of welding between the work material and the dies. A good mold material should not react with the work material and should not generate any gas. The coating should be easy to apply and should have a good binder so that it is not washed into the casting when the molten metal is poured into the die or mold. As can be expected, the mold coatings have refractory materials as major components. Such coatings are used extensively in ingot molds and over chills, and the experience would be useful in selecting a coating in squeeze casting also.

Bidulya and Smirnova[21] contend that pressures of 10,000 psi or less will do for steel squeeze casting, and even lower pressures are adequate for cast iron squeeze casting. They claim die lives of 1250-2500 parts, which weighed 44 lb, using 1020 steel as a die material.

In a study of die life for steel squeeze casting, Ashtakov et al.[22] used a variety of different die materials for the squeeze casting of a steel tractor component. The chief problem with type 1020 steel as a die material was its deformation and the consequent loss of punch tolerances. They claim that 3Kh2V8 (H21, nearest U.S. equivalent) heat treated to 39-40 R_C, was the best punch material (die life over 600 parts), with the failure mechanism being one of heat checking.

Bidulya and Zlodeev[13] have discussed squeeze casting of 1045 steel to make a hub weighing 115 lb and a hydraulic press nut weighing 83.5 lb. They have also made references to some smaller test castings and have offered some general comments about the process.

Ryzhikov et al.[14] have described squeeze casting of 11.0 to 26.4 lb inserts in a tool steel to be used in forging dies. The melt preheat temperature was 120°F above liquidus, and the die preheat temperature was 390°F. For a 15.4 lb component with 2.16 in. thick walls, the solidification time under pressure was 20 to 25 sec.

Zubov and Began[15] used a die system which is comparable to that used for transfer molding of plastics. They squeeze-cast type 321 steel flanges of 7.5 lb weight and 1045 steel spur gears of 7.0 lb in weight. With their die system, the molten metal was poured into a receiving chamber below the die cavity. When the top die moved down, it pushed the lower die down against some springs, thus forcing the liquid metal from the receiving chamber into the die cavity. The quality of the product was found to be much better, and it was free of any laps and folds.

In making the flange in this fashion, the forming pressure was 13,100 psi and the duration of pressure was 18 sec. The temperature of the molten metal was 2910°F; the working temperature of the dies was 390°F. A cylinder oil was used as the lubricant, and the bottom of the receiving chamber was coated with an 0.012 to 0.020 in. layer of ordinary fire clay chill mold dressing.

As mentioned above, data on the preheat temperature of the dies are recorded by several different investigators. However, actual measurements of the surface temperature of the dies during squeeze casting ferrous parts are somewhat rare. This type of work has been conducted by Deordiev at al.[16] and to a limited extent by Cherniy and Zubov.[17] The conclusions reached were collars, and gear blanks. He has also considered a special die design for production of components such as turbine blades. Essentially, the design consists of transferring the molten metal by means of a punch from a pouring well to the die cavity proper. Then, final forming and consolidation are conducted at a temperature where the metal is close to a plastic state. The advantage of such a die design is a relatively superior surface finish and freedom from any tearing.

According to the work reviewed by Bidulya,[2] the pressure should be applied at the moment of zero fluidity, which can be interpreted as the stage when continuous solid-phase skeletons are formed in a two-phase alloy. The zero fluidity temperature of steel is approximately midway between the liquidus and the solidus. At this moment, the punch can work the material with the least pressure and obtain a sound and homogeneous macro-structure. If pressure is applied earlier, the crust formed on the surface of the metal is ruptured and the molten metal inside flows over the ruptured crust forming defects. Bidulya also mentioned a temperature of pouring of about 90°F above the liquidus and refers to squeeze castings weighing up to 220 lb. He also states that after suitable heat treatment the strength, ductility, and toughness of squeeze castings were 10 to 15% higher than for the rolled steel and 20 to 30% higher than cast steel when similar compositions are considered. The yield of steel in squeeze casting can reach 90 to 95%, which is far in excess of other techniques such as forging, welding, or casting.

Bobrov et al.[3] have stressed the importance of accurately metering the melt volume. In their work the molten metal was displaced by lowering a float of known volume into the furnace causing it to overflow. The melt temperature was maintained 125 to 245°F above the liquidus, and the forming pressure was 12,800 psi. The holding time in the die was 5 to 15 sec before applying pressure and 8 to 20 sec under pressure. Experimental castings weighing 8.2 lb were made in steels of grades 1030, 420 stainless steel, and 321 stainless steel.

5. Ability to utilize both cast and wrought compositions of work materials.

6. Substantially increased production rates in comparison with conventional casting techniques.

7. Possibility of substantial cost reduction in comparison with sand castings because of items 2 and 3 and in comparison with forgings because of the lower cost of the melt stock used for squeeze casting instead of the wrought materials used for forging.

8. Improvement in product quality such as the surface finish and mechanical properties in relation to sand castings. The generally harder as-squeeze cast material may also, in some cases, eliminate the need for further heat treatment.

2.2 Published Work

There are many references, generally in Russian publications, on squeeze casting. However, in this brief review we shall only refer to a few selected articles on ferrous squeeze casting.

Plyatskii(1) has discussed investigations on squeeze casting of cast irons. These are typically conducted at temperatures of 2300° and 2350°F using gray cast iron dies. The applied pressures for squeeze casting cast irons are quite low, being only of the order of 300 psi. Even such low pressures give a substantial improvement in product quality in terms of bend strength and tensile strength. The process is used in large-batch production of seats and valve bulk covers for gas engine compressors.

Plyatskii(1) has also considered squeeze casting of different items of steels weighing up to 44 lb. The die material was usually a carbon steel of the 1020 type and capable of die life up to 2000 or 3000 parts depending on the product and the precision required. The items he has mentioned are drill bits, the solidifying material, the pressure level and its duration, and the tooling temperature. The melt temperature should be kept low to get good die life, but it should be high enough to give a good surface finish and interr 1 quality to the product. The time delay should be such that the pressure is applied on the partially solidified material and not while it is still completely molten. In large components, especially of nonferrous materials, the time delay required could be of the order of half a minute or more whereas in small ferrous components, often the time delay is a matter of a few seconds only. The pressure level is affected by the work material as well as the complexity of the component and should, in general, be selected to the lowest possible level consistent with good internal structure of the squeeze casting. Essentially the same comments apply to the duration of pressure which should be long enough to complete the solidification under pressure but not so long that it could affect the tooling life adversely. The tooling temperature also depends on the work material and the part complexity but is normally in the range of about 400° to 700°F.

The principal advantages of the squeeze casting process can be listed as follows:

1. Ability to produce parts with complex profile and thin sections beyond the capability of conventional casting and forging techniques.

2. Substantial improvement in the material yield in comparison with sand casting because of the elimination of risers and gates.

3. Elimination of the labor associated with sand casting such as for molding, trimming of risers and gates, and cleaning of casting.

4. Substantial reduction in pressure requirements in comparison with conventional forging while at the same time increasing the degree of complexity that can be obtained on the parts.

itself then solidifies under essentially atmospheric pressure. Therefore, the quality of the ferrous die castings is quite poor. Porosity at the center of the casting is quite common and, as a result, the mechanical properties of the product are also poor. There is loss of material because of the runner system needed for die casting. Additionally, the problem of die life becomes severe because of the need to push the molten steel through narrow openings. Current status of the art[8,9] allows production of only small parts weighing a few pounds at the most. Furthermore, the machines required for ferrous die casting would be expected to be very elaborate and expensive. As in any die casting process, high clamping forces will be needed to hold the two halves of the dies together against the high injection forces although the pressure during solidification of the workpiece is quite small. Considering the principles of squeeze casting and various other information discussed below, the capability of squeeze casting is far superior to that of ferrous die casting in terms of product quality, product size, and cost of the equipment.

Squeeze casting also differs from rheocasting.[10-12] Unlike the former, the rheocasting process involves several different steps. Basically, it consists of agitating the molten metal until approximately half the metal solidifies. Then, the semi-solid material is transferred into the forming dies and subjected to the forming operation. While several advantages have been claimed for the process, as far as can be judged thus far, the work has been limited to making of small components from non-ferrous materials or cast irons. Recent major efforts[11] have concerned development of tooling or equipment for various phases of rheocasting. At least so far, the process has not been applied to fabrication of complex steel components of the type that are under investigation in this program.

The main process variables in squeeze casting are the melt temperature, the time delay before the pressure is applied to

The decision to make the component with a through-hole on both ends was dictated partly by the need to have maximum material utilization and partly by the desire to limit the plan area of the component to ensure that adequate pressure was available with IITRI's 1000-ton press.

A very important consideration in making the tubular preform is the technique of removing the casting from the dies. The casting has a natural tendency of shrinking onto the punch that forms the inside detail. Because of the rigidity of the punch, the casting would crack badly if it is allowed to shrink onto the punch. The sleeve type of design (Fig. 4c) ensures that, at the end of the squeeze casting operation, the ram can be retracted quickly, with the sleeve forcing the casting to remain in the lower die. The casting is not obstructed by the punch and can shrink freely except at the ejection pin at the partially closed end. The casting can then be pushed up from the lower die by the ejection pin and stripped off the ejection pin by inserting a stripping tool between the top of the lower die and the lower surface of the partially closed end of the casting. This was the design selected for the subject program. The corresponding target squeeze casting geometry is shown in Fig. 5. The estimated weight of the squeeze casting is 147 lb.

Another alternative design involved making a cup-shaped casting with one end closed (Fig. 4d). The tooling is very simple with this casting shape. However, the material yield is poor in relation to the alternatives discussed above. In addition, the cup-shaped casting has a large plan area which would reduce the maximum pressure capability to less than 10,000 psi with IITRI's 1000-ton press. This pressure may be marginal for obtaining a good quality casting. Therefore, this design was eliminated from further consideration. A number of other approaches were also studied briefly. One of these involved supporting the ejection pin in the design in Fig. 4a on a removable plate. At the end of the casting operation, the insert could be moved out and the ejection pin pressed down using the

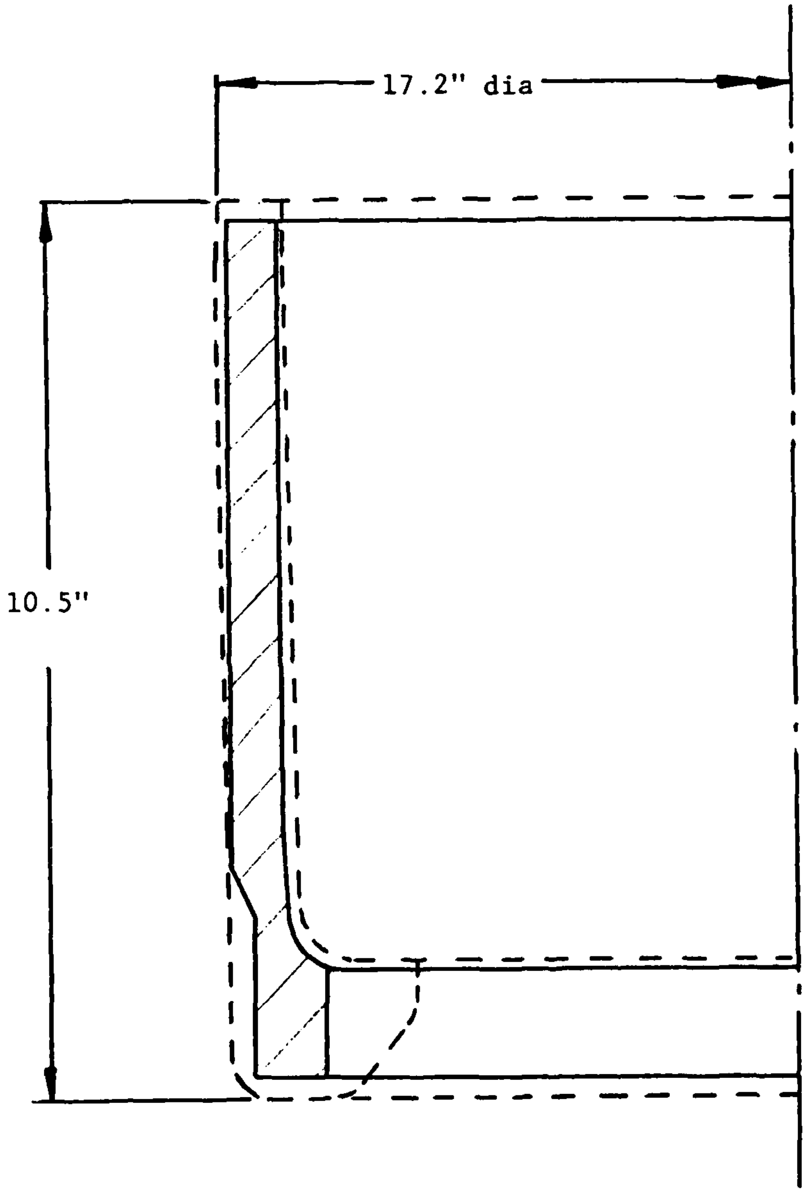


Figure 5

Target Geometry (dotted) for Preform Squeeze Casting
(Solid lines show machined contour.)

punch to free the casting from the ejection pin. Such ideas were rejected because of the complexity they would add to the tooling and the casting operation.

As with the forward dome, H13 die steel was selected as the material for all the major tooling components. The die set for the preform is shown schematically in Fig. 6.

3.3 Dimensional Considerations

The final dimensions of the die cavity depend on the thermal expansions of the tooling and the squeeze casting and on the machining allowance left on the squeeze casting. Since the tooling expands as it reaches squeeze casting temperatures and the squeeze casting itself (forward dome or case preform) shrinks during cooling to room temperature, the initial room-temperature die dimensions are a function both of the thermal expansion of the die materials and of an anticipated shrinkage factor for the squeeze casting. For example, with H13 die components, the die dimensions will increase 0.0034 in/in at an operating temperature of 500°F above room temperature. The magnitude of shrinkage of the squeeze casting depends on whether it is allowed to shrink unrestricted inside the die cavity or shrinks onto a rigid punch. In the first case, the casting would shrink all the way from the temperature at punch pull-out (usually about 1600°F) down to room temperature. In the second case, shrinkage will begin to be experienced only when the temperature drops to a value (1000°F typically) such that the yield stress of the material at that temperature exceeds the hoop stress in the casting due to contraction onto a rigid punch, thereby making the shrinkage elastic. For dimensional calculations during die design, it was assumed that the squeeze casting would shrink during cooling through about 1200°F, which resulted in a casting shrinkage factor of about 0.010 in/in.

The die cavity dimensions at room temperature are found by equating the casting dimensions at 1200°F to the die cavity dimensions at 500°F above the ambient. Thus, for a 10 in. room-

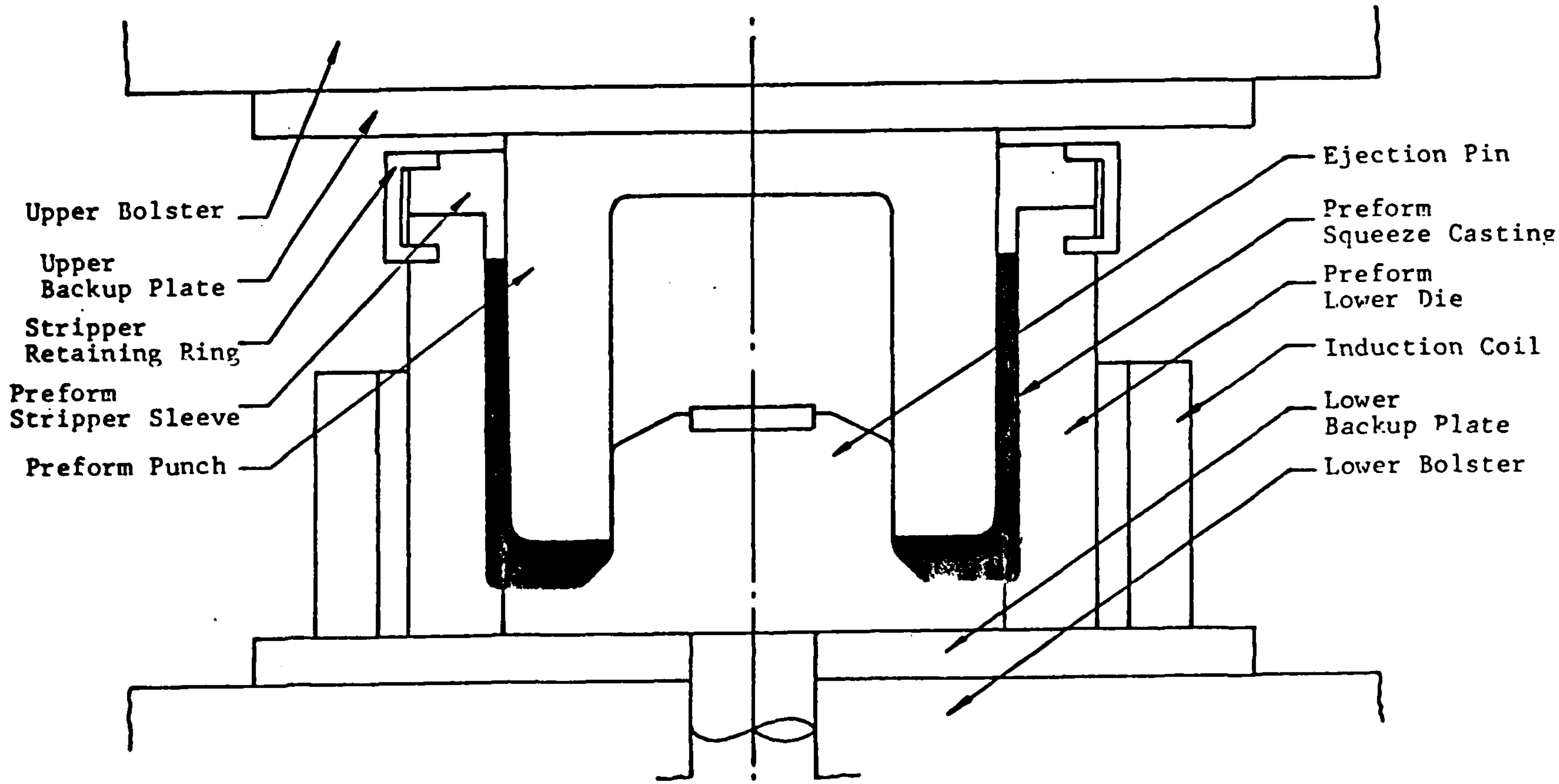


Figure 6
Schematic of Preform Die Assembly

temperature dimension of the squeeze casting (case preform length = 10 in.), the casting dimension at 1200°F above room temperature would be 10.100, based on a 0.010 in/in thermal expansion. This, then, is the die cavity dimension at 500°F above R.T. The die cavity dimension at room temperature would be less than the above by 0.034 in. since the dies contract by 0.0034 in/in. Consequently, the room-temperature dimension of the die must be 10.066 in. to result in a squeeze casting dimension of 10.000 in.

4. EQUIPMENT AND PROCEDURAL DETAILS

4.1 Hydraulic Press

The HPM 1000-ton press has a variable capacity hydraulic pump and a nitrogen accumulator. Press speeds from 0 to 600 ipm can be achieved by operating the press with either the hydraulic pump or the accumulator (for the preform casting) as the supply of high-pressure oil. The control of the load and ram movement is achieved manually during slow-speed operations (for the forward dome casting) and electrically with switches and hydraulic pressure sensors for high-speed work. The movement of the ram can be stopped and also the ram speed changed from fast advance to a preselected speed by electrical switches and cams. The press daylight is approximately 48 in. with a 24 in. stroke, and the bed measures 50 in. x 42 in. wide.

4.2 Melting and Melt Transfer Facilities

A 150 lb capacity, high-frequency induction melting furnace was used for all the squeeze casting trial melts. The furnace consists of a water-cooled induction coil in which is mounted an alumina liner, which is fixed inside the coil using refractory plaster (X-9). The alumina liner is really a crucible about 13 in. high and 8 1/2 in. diameter with a brimful capacity of 164 lb of steel. A transfer ladle, with arrangements for preheating, is employed to carry the molten metal to the 1000-ton HPM press.

The melt transfer system for the preform is very important since, in view of the thin wall of the casting, the time available for handling of the 150-160 lb of steel melt, closing of the dies, and making of the casting is relatively short. The melt transfer system which was finalized is shown in Fig. 7. It comprises a ladle cart which can be moved on rails. The melt is transferrred from the melting furnace to a ladle which can then be moved to the press by means of an overhead crane and placed on the ladle cart. Then the ladle can be moved into the work area of the press by rolling in the ladle cart on the rails, and the ladle can be quickly tilted to transfer the melt into

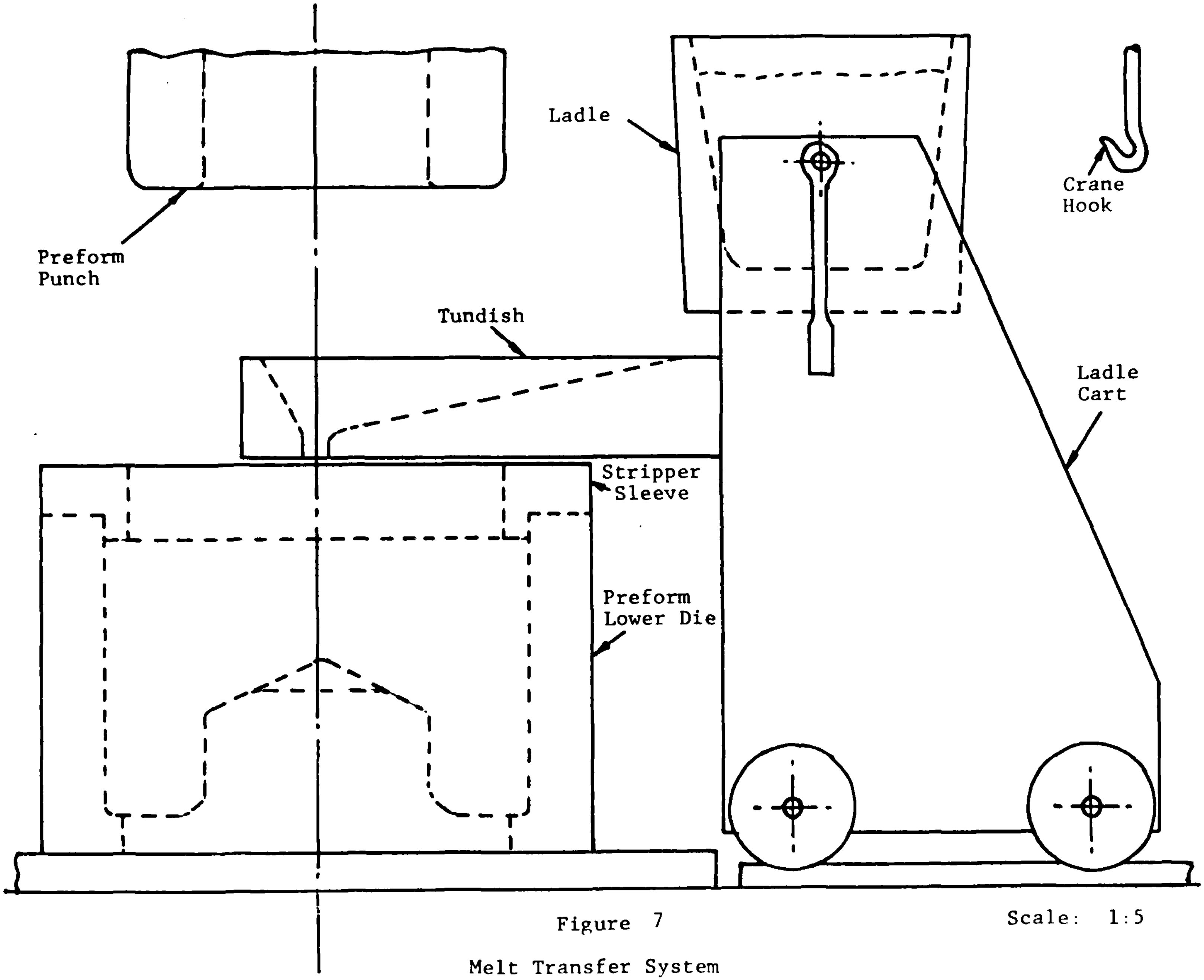


Figure 7

Melt Transfer System

the dies. The ladle and cart can be retracted, and the squeeze casting operation can begin.

4.3 Melting Techniques, Composition Control, and Melt Transfer

D6AC steel melting stock in the form of chunks weighing 10-30 lb is charged into the induction furnace gradually until the entire charge melts.

Argon gas is constantly flushed through the furnace lid during the entire melting period of about 1 to 2 hr depending on the size of the melt. After a small addition of ferro alloys and deoxidation with aluminum, the molten steel at about 3150°-3200°F is poured into a preheated transfer ladle, lifted by an overhead crane, walked to the 1000-ton press, and set in the ladle cart fitted with a preheated launder. The temperature is allowed to drop to 2800°-2850°F when the metal is poured by bringing the ladle cart into the position and tilting the crucible such that the molten steel pours into the center of the pouring cup located at the center of the lower die.

The quantities of additions to the melt were decided on the basis of a few initial squeeze castings by analyzing their composition.

4.4 Die Heating

The temperature of the squeeze casting die is important because a preheated die will delay solidification of the molten metal until pressure can be applied. However, the maximum preheat temperature must be safely below the tempering temperature of the H13 die material, whereas a minimum temperature of 350°F is required for reasonable die toughness and to minimize thermal stresses.

The lower die is heated by an induction coil surrounding it, to about 450°-500°F. The punch is heated by means of a portable set of seven gas burners arranged uniformly around it to about 350°-450°F. The temperature of the lower die is automatically controlled, but the proper temperature of both the dies is ensured by measuring it periodically by means of a surface pyrometer.

In production, because of quick succession of the squeeze castings, the die temperature can be maintained without heating once the series is started. In fact, there may be need for cooling the dies to maintain them in the desired temperature range.

4.5 Die Pretreatment and Mold Wash

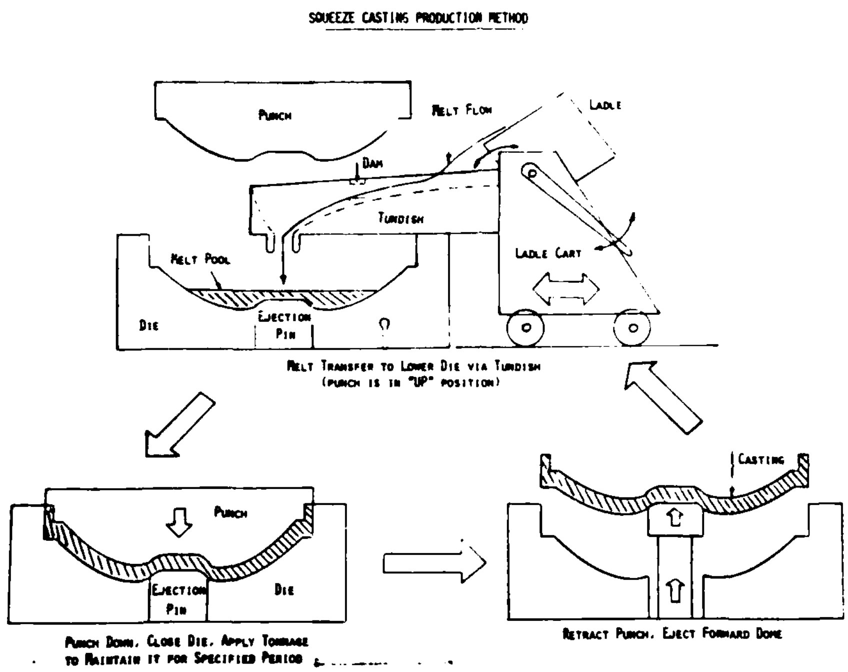
Freshly machined die steel surfaces must be conditioned before squeeze casting to minimize the possibility of the squeeze casting welding to the die surface. This conditioning consists of heating the die steel component to approximately 600°F to give the surface a protective oxide layer. With use, the die steel becomes increasingly oxidized and the resistance to welding increases. However, an additional coating of mold wash is generally required to further protect the dies against welding.

A graphite-base lubricant is sprayed on the die surfaces to provide a protective coating. To further prevent welding and reduce heat transfer, a first layer of ceramic mold wash (Nalco-839P) is sprayed on the lower die surface followed by the graphite-base lubricant.

4.6 Experimental Procedure

4.6.1 Forward Dome

The schematic of the forward dome die assembly is shown in Fig. 2. The following figure (Fig. 8) shows how such a part is squeeze cast; the sequence being, pouring the melt into the die center, lowering the top punch onto the molten metal, and "forging" the melt into the final configuration. Upon solidification, the punch is raised and the casting removed from the die. Melting techniques, composition control, melt transfer, and die preparation have been dealt with in detail in the following



Neg. No. 47815

Figure 8

Schematic of Squeeze Casting Process for Forward Dome section on the case preform. The near-net shape squeeze casting of the forward dome weighs about 60 lb. Pouring accuracy, length of pour time into the die, and cleanliness of the melt were found to be very important parameters to control. To make sure the melt poured precisely, the pour crucible and launder are mechanically locked into position just prior to casting. Pour time of about 10-15 sec has been found to be optimum for good results.

To prevent the slag flowing with the melt and getting plastered to the die wall producing defective castings, "dams" are built in the pour crucible and the launder to hold it back. An optimum value of 5-8 sec for the load duration has been found to produce crack-free castings.

4.6.2 Case Preform

The schematic of the preform die assembly in the closed position is shown in Fig. 6. The schematic of the melt transfer system is shown in Fig. 7. All die cavity surfaces that may come in contact with the casting are prepared by controlled oxidation, ceramic spray, and graphite coating, in that order. Ceramic spray is not used for the top half of the die.

The melt stock is melted in a 150-lb induction melting furnace under an argon blanket, given the required ferroalloy additions, and deoxidized with aluminum. At about 3150°-3200°F it is poured into a preheated transfer ladle which is then carried by an overhead crane to the ladle cart near the press. Temperature is checked again, and when it falls to 2800°-2850°F, the ladle cart is pushed into the die set (which is at this point in open position). The ladle is tilted to transfer the melt into the lower die via the launder, the ladle cart is retracted, the dies are closed, and full load of 1000 tons is applied to make the squeeze casting. The dies are then opened with the stripper sleeve stripping the casting off the punch as it retracts and keeping the casting in the lower die. The retainer ring is then removed, and the sleeve is taken off. The ejection pin is then moved up to push the casting out of the lower die. Two semicircular stripping tools are then pushed between the lower surface of the casting and the upper surface of the lower die, and the ejection pin is pulled down to strip the casting off the ejection pin and remove it from the press. The entire cycle is then repeated for the next squeeze casting.

5. FORWARD DOME AND CASE PREFORM SQUEEZE CASTING SERIES

Both of the PATRIOT components that were investigated under this program--namely, the forward dome and the case preform--were squeeze cast successfully to result in sound, good quality castings that were essentially free of porosity, inclusions, and surface imperfections. The details of this work are presented below.

5.1 Forward Dome Squeeze Casting Series

Sixty-pound induction-heated melts of D6AC alloy steel (nominally 0.45% C, 1.0% Cr, 1.0% Mo, 0.55% Ni, balance Fe) were poured into a crucible at 3200°F and walked about 100 ft in one minute to IITRI's 1000-ton hydraulic press into which the dome die set had been installed. The long walk permitted too much cooling of the molten alloy such that it was already partially frozen in the crucible, poured sluggishly into the die, and then did not forge properly, coming out of the die only partially developed (Fig. 9). To overcome this initial problem, the quantity of melt into the crucible was increased to 100 lb. This was found to be satisfactory, to the extent that it was actually necessary now to wait about 2 min at the press for the temperature to drop to 2900°F, at which time the metal was poured into the die. In the meantime the die had been prepared for squeeze casting by coating it with graphite as a lubricant plus a ceramic spray as a parting and diffusion-inhibiting agent and preheating it to about 450°F. Approximately 60 lb of molten alloy was first poured into the die cavity and, while pressure was being applied to it, the balance of the melt in the crucible was cast into reusable pigs, leaving the crucible ready for the next melt.

As soon as the 60 lb pour was completed, the top punch (also at 450°F) of the die set was brought in contact with the molten pool of steel and a pressure of 13,600 psi was applied for 1 sec, then reduced to 10,900 psi and held for 4 sec. (The higher initial pressure was developed due to press tonnage overshoot upon

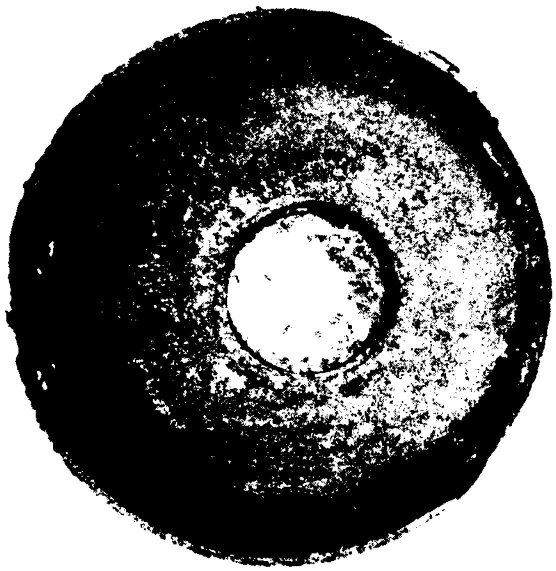


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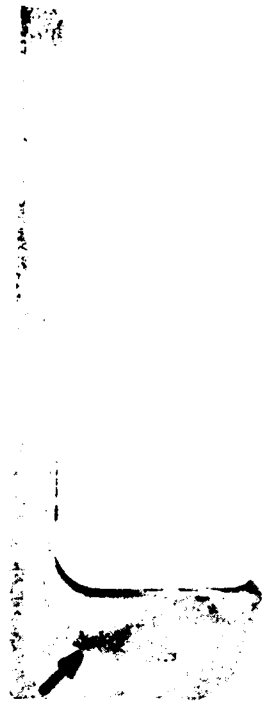
Figure 9

Forward Dome Casting Partially
Developed Because of Too Low
Pouring Temperature



Neg. No. 47331 0.4X

(a)

Neg. No. 47332 2.5X

(b)

Figure 20

Macroetched Cross Section of Preform Squeeze Casting No. 23.
(a) Overall section view showing porosity in web region;
(b) lap formation in wall region.

casting out of the lower die. Two semicircular stripping tools are pushed between the lower surface of the casting and the upper surface of the lower die, and the ejection pin is pulled down to strip the casting off the ejection pin and remove it from the press.

5.2.1 Melt Transfer

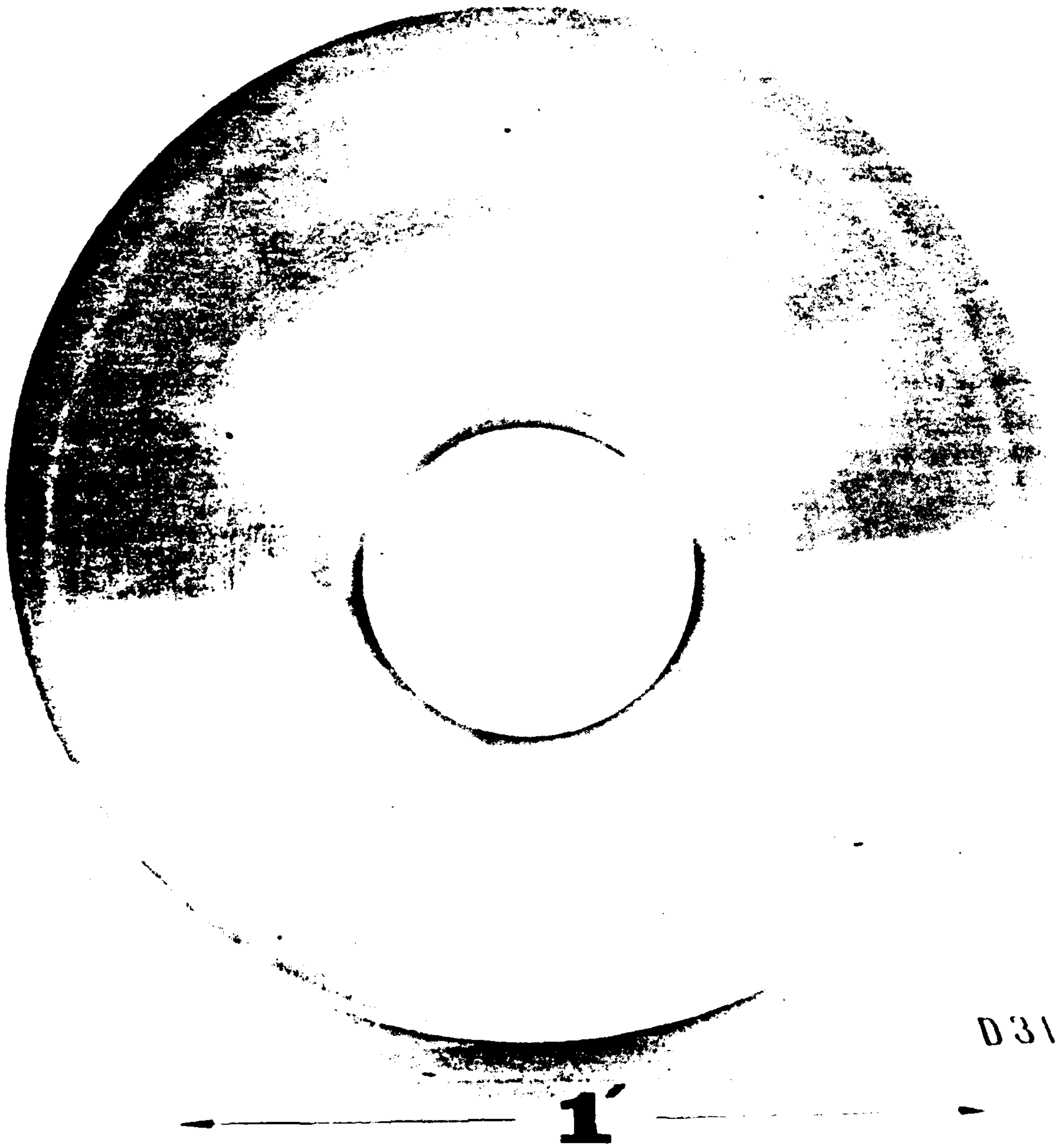
The initial castings were poured at a temperature of about 2900°-2950°F. The resulting castings showed extensive surface imperfections and cracks as well as cold laps and internal porosity (Fig. 20). It was felt that much of this could be eliminated by using a higher melt temperature. Castings poured at 3000°F did present a better surface appearance, and one casting (No. 20) which was sectioned and metallographically evaluated was essentially free of porosity. Figure 21 shows this section as well as photomicrographs of samples taken from various locations within the casting.

However, the higher pouring temperature resulted in frequent welding to the die necessitating reconditioning, the latter by weld deposition and machining. The deliverable squeeze castings of the case preform were later poured at 2800°-2850°F utilizing information and experience gathered from the forward dome series of experiments. This range of temperatures proved to be optimum with respect to casting internal quality as well as die life.

Surface imperfections were found to depend more on melt quality, cleanliness, and the speed and accuracy of pouring, and good squeeze castings were produced by paying careful attention to these parameters.

5.2.2 Time, Accuracy, and Cleanliness of the Pour

Proper channeling of the melt into the die cavity was found to be of the utmost importance in producing sound castings with no casting-to-die welding. It was necessary to use an accurately positioned pouring cup (Fig. 22) to achieve the desired results.



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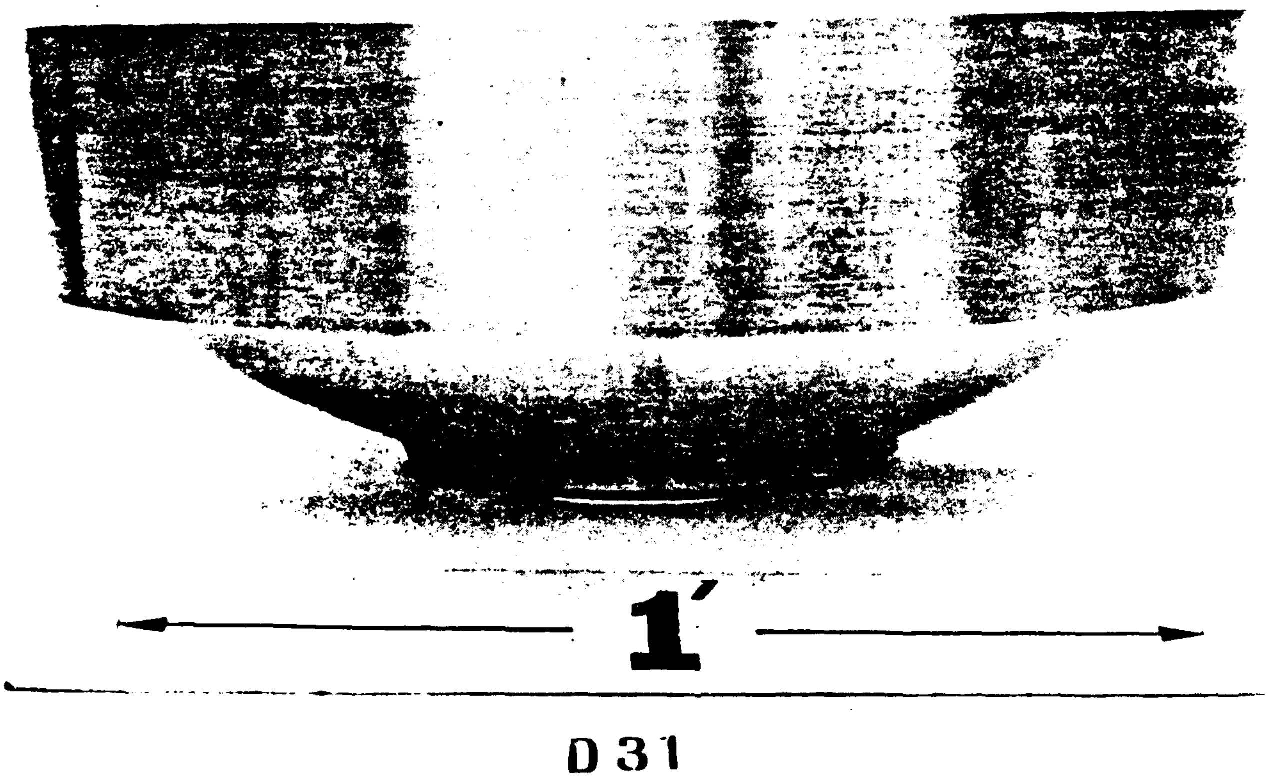
(c)

Figure 19 (cont.)



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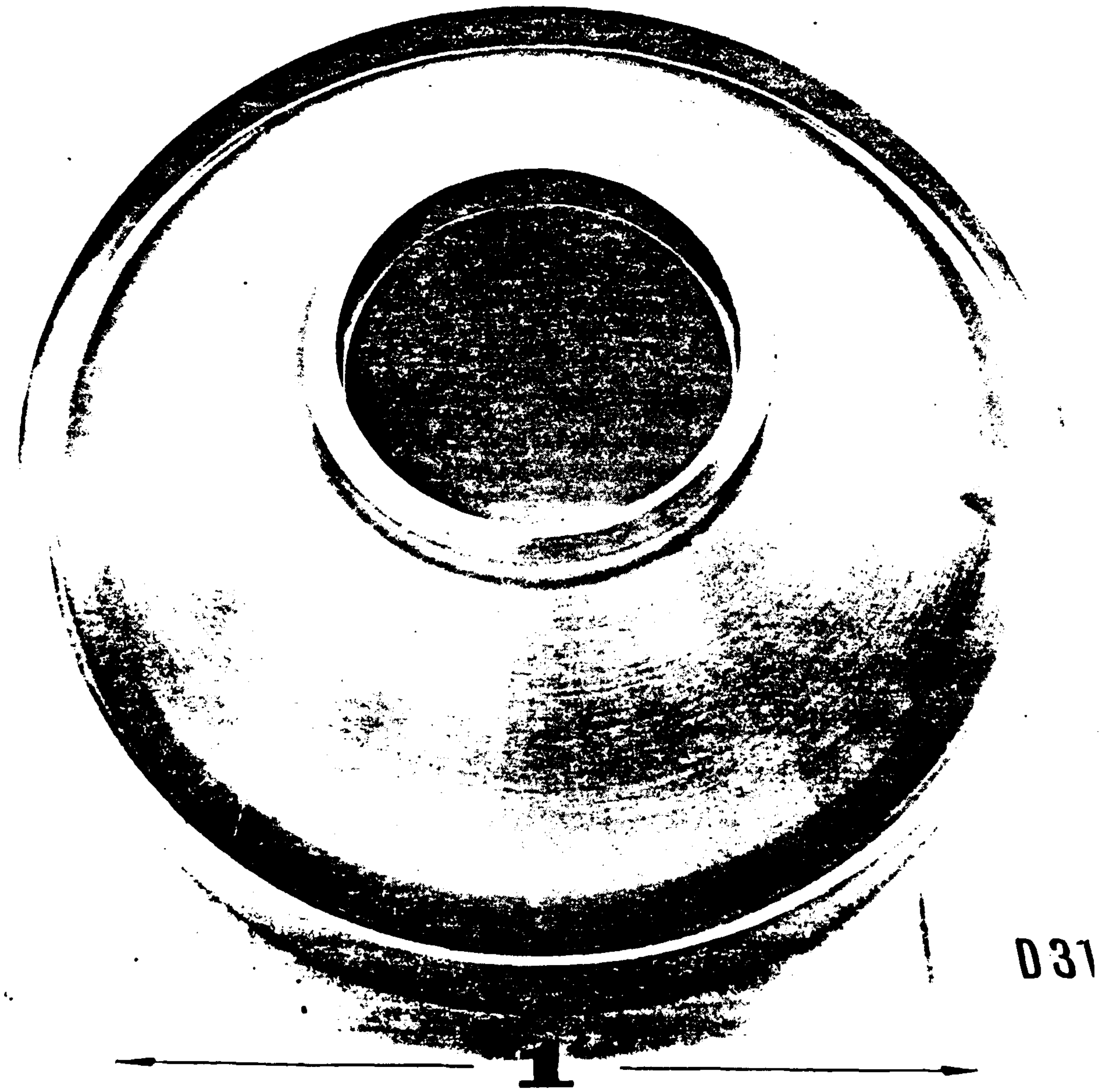
(b)

Figure 19(cont.)



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(a)

Figure 19

Three Views of Finish-Machined Forward Dome
Squeeze Casting Showing Excellent Surface Details

Neg. No. 47350 100X

Figure 17

Typical Martensitic Structure of a Forward Dome Casting

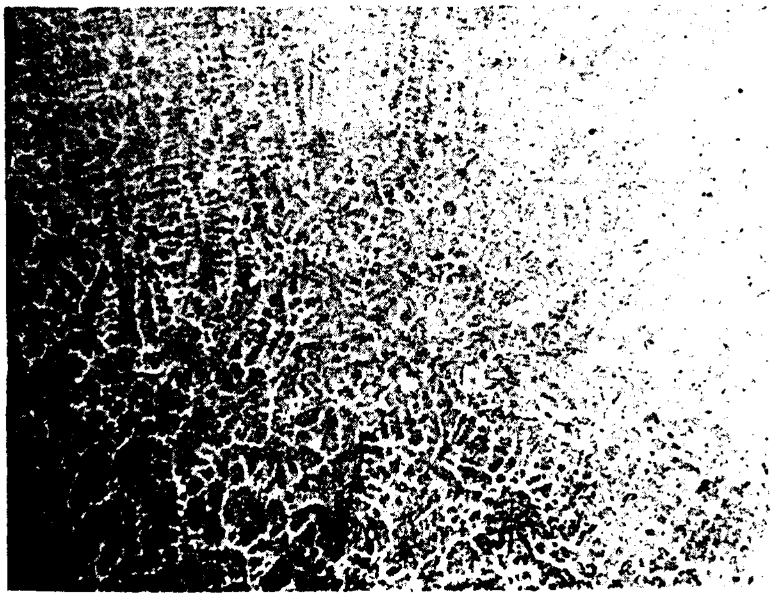

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Figure 18

Localized Dendritic Section of a Forward Dome Casting ceramic molding placed on the top of the ejection pin for each casting (Fig. 16).

5.1.5 Microstructures of the Forward Dome Castings

Figure 17 is a representative microstructure of the castings. The basic structure is martensite. Figure 18 shows a section of a casting with a dendritic pattern; however, sections with this microstructure are not predominant in the castings. A conventional heat treatment can remove this structure replacing it with tempered martensite.

5.1.6 Testing and Machining of Finished Castings

Once the castings were ejected and cooled, they were then deburred, weighed, sandblasted, and spray coated to prevent rusting. Representative samples were radiographed, and this revealed satisfactorily squeeze-cast domes showing no cracks or holes. Five squeeze castings, in all, were sent to Redstone Arsenal for evaluation, of which four were in the as-squeeze-cast condition. An additional one was machined to specification and is shown in Fig. 19.

5.2 Case Preform Squeeze Casting Series

For the case preform component, the melting and melt transfer procedures were essentially the same as for the forward dome. Basically, it involves heating the tooling to the desired temperature in situ in the press, melting the work material in an induction melting furnace and transferring it to the ladle cart near the press using a preheated ladle, pushing the ladle cart into the die set (which at this point is in open position), tilting the ladle to transfer the melt into the lower die via the launder, retracting the ladle cart, and then closing the dies and applying load to make the squeeze casting. The pressure applied to the melt is 12,400 psi maintained for 15-20 sec. The dies are then opened with the stripper sleeve stripping the casting off the punch as it retracts, and keeping the casting in the lower die. The retainer ring is removed, and the sleeve is taken off. The ejection pin is then moved up to push the

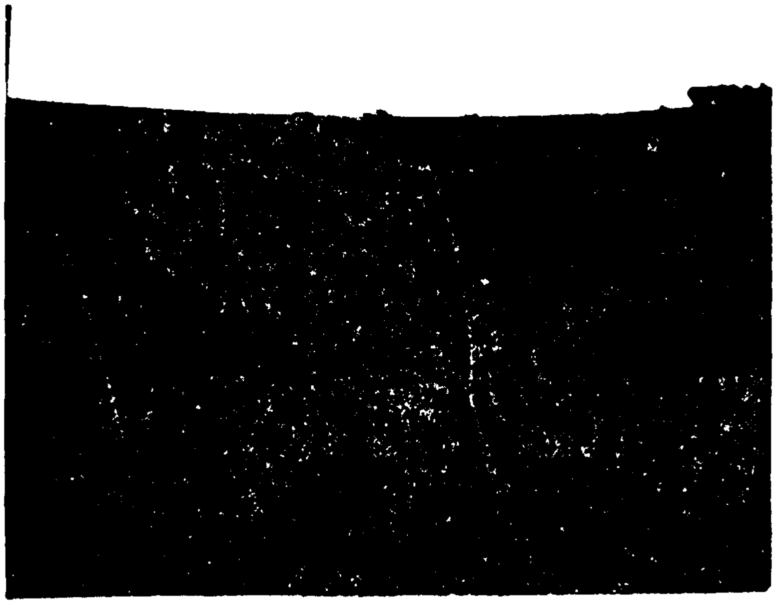

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Figure 15

Skirt Crack Development During Cooling of Dome Casting, Caused by Too Long Duration of Pressure

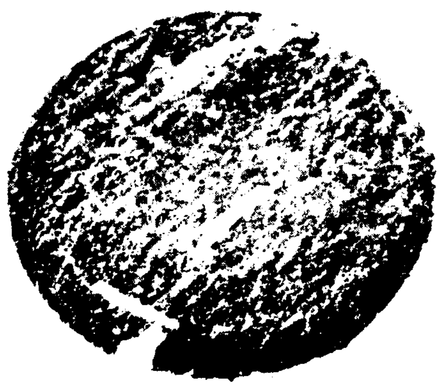

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Figure 16

Expendable Ceramic Molding Placed on Top of Ejection Pin for Each Dome Casting. This nonreactive piece prevented welding of the casting to the die.

produced relatively minor discontinuities in the casting surfaces which machined out almost totally.

5.1.3 Pressure Level and Duration

The pressure applied to the melt immediately after finishing the pour was limited to the maximum developed by our 1000-ton press. Actually, the level went to 1500 tons (13,600 psi) for 1 sec, then dropped to 1200 tons (10,900 psi) and was held for 4 sec. Lower pressures did not produce fully developed castings nor eliminate all internal porosity; hence the use of maximum attainable loads. The pressures used, although at this maximum, were still below those quoted in the Russian literature, namely, up to 20,000 psi.

In work on other steel castings, times at pressure as long as 20 sec have been used. With the forward dome, however, vertical cracks in the skirt (thin wall) were formed when long pressure times were used. It appeared that the top punch expanded rapidly as the molten steel was being forged into the casting shape. The casting itself was losing heat to the tooling and was therefore contracting. Hence, these opposing forces appeared to cause the casting to pull itself apart (crack) to relieve the stresses (Fig. 15).

This problem was overcome by reducing the time at pressure from 20 sec to 5 sec, which was just long enough to ensure complete solidification of the casting under full pressure. Under these conditions, the punch did not expand as much and the casting did not contract as much, thus reducing the shrinkage stresses within the casting.

5.1.4 Prevention of Welding Between Casting and Die

Accuracy of pour was needed, as noted previously, to prevent welding of the casting to the die. However, when accurately pouring a large quantity of molten steel from even a 6 in. height, sprayed-on alumina die coatings tend to erode with subsequent welding. This was overcome by use of an expendable, nonreactive

Neg. No. 47482 0.2X

Figure 13

Properly Poured Casting Which Shows
No Gross Discontinuities

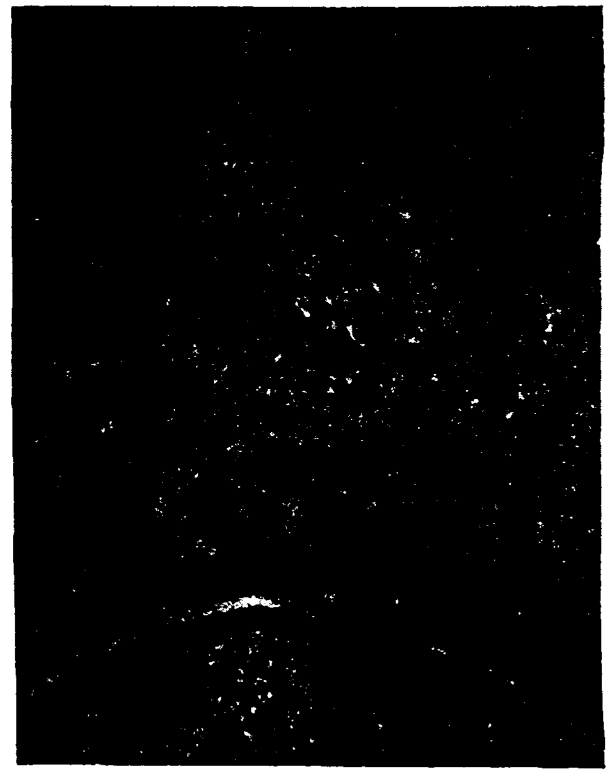

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Figure 14

Slag Imperfections in Dome Casting Wall

parameters to control. These conditions cannot be stressed too strongly. If the pour was not dead center into the die cavity, nonuniform liquid fill into the die ensued. Turbulence, splatter on the die wall, and erosion of the diffusion-inhibiting parting agent were encountered leading to defective castings and welding of the casting to the die. To make sure the melt poured precisely on target, the pour crucible and launder or tundish were mechanically locked into position just prior to casting.

Time of pour was experimentally determined, the rationale being the shorter the pour time and consequent residence in the die cavity, the better for the final casting. Shorter times meant a lesser degree of die wall freezing, minimum reaction between melt and die, and less heat transfer to the die. Too much of a solid crust or "skull" formation created too high a resistance to the squeeze pressure and improper die fill. Long-term reaction between melt and die wall could lead to welding, while overheating the die parts would lead to lower die life plus distortion of die components under the forging stress.

A pour time of 6 sec was tried first, but found to be too rapid. Turbulence of the melt was encountered, and large particles of slag passed over the "dam" set up in the tundish, into the die and onto the die wall. (This is described shortly.) A time of 30 sec proved too long, the molten metal coming into the die in wavelets which produced unacceptable layers in the casting (Fig. 12).

The pour time was reduced to 10 sec which was found acceptable and was standardized into succeeding runs (Fig. 13).

Cleanliness of the melt refers to removal of the dross or slag prior to pouring. If this were not done, particles of slag would plaster themselves to the die wall and become major surface defects in the final casting (Fig. 14). This problem was overcome by placing a doctor or scraper blade over the melt in both the pour crucible and the launder. These "dams" held back almost all the dross. The few particles that did get through

Neg. No. 47229 0.4X

Figure 11

Macro Sections from Two Dome Castings, (top) One with Internal Defects Produced by Too Low Casting Temperature and (bottom) One Poured at Proper Temperature

Neg. No. 47494 0.5X

Figure 12

Casting Defects Caused by Too Long a Pour Time

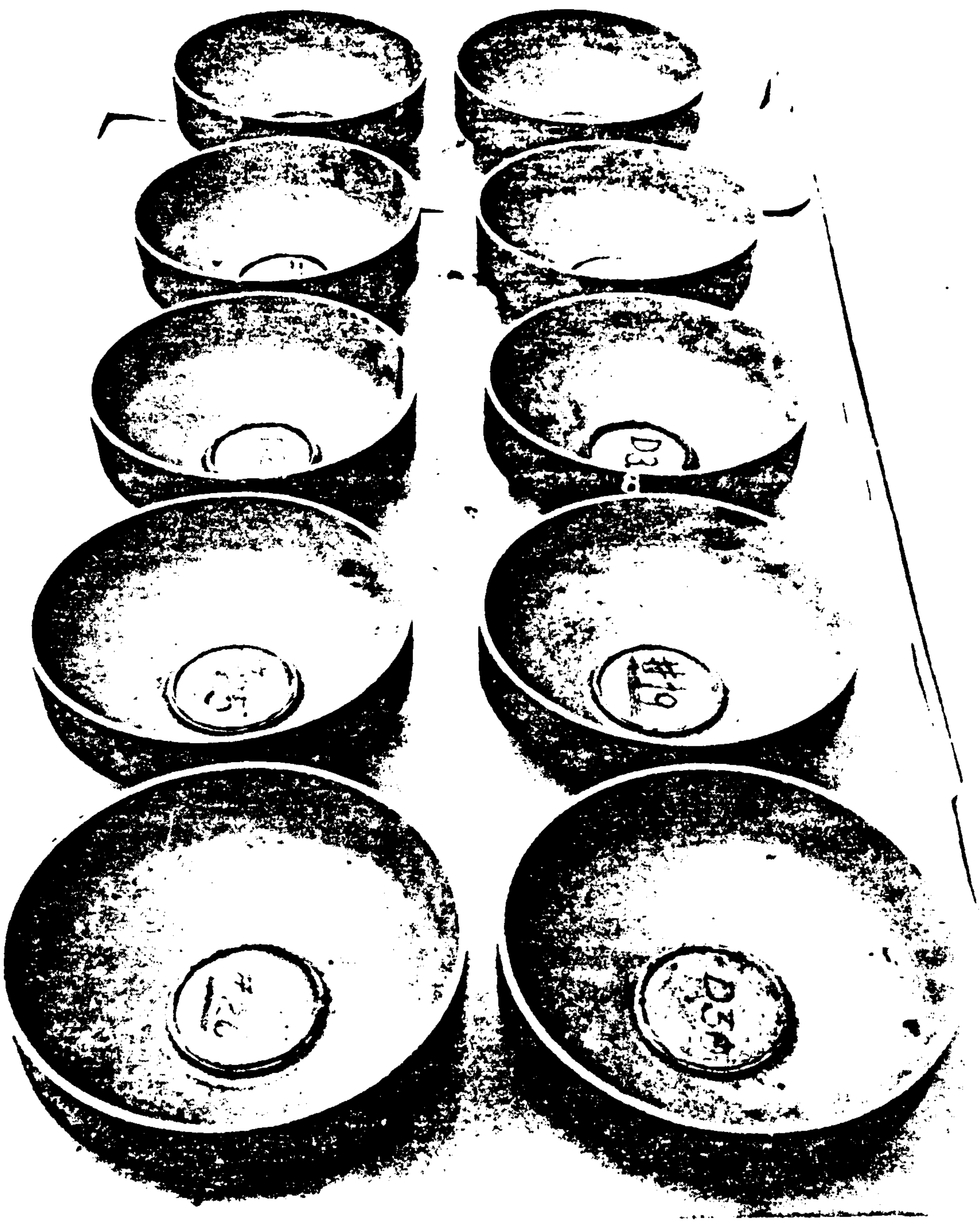

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Figure 10

Ten Forward Dome Squeeze Castings Produced, Top View impact, rather than by design.) This pressing or squeezing flowed the molten metal into the entire die body cavity while the holding time permitted the steel to solidify without the formation of cracks or internal porosity. Pressure was then released, the top punch raised out of the die body, and the casting itself removed from the tooling. This technique was used to consistently produce good castings, making a total of 10 from which five were selected for shipment to Redstone under the requirements of the contract (Fig. 10).

Although the preceding sequence of events seems rather straightforward and the final processing techniques worked out for squeeze casting rather simple to institute and control, a number of problems had to be overcome (some straightforward, others difficult) before we were able to proceed and make the deliverable items. Some of these problems are discussed below.

5.1.1 <u>Temperature of the Melt</u>

A few experiments were needed to determine the correct melt temperature. As previously noted, too low a temperature did not allow for a full casting to be developed. Also, excessive porosity existed in the upper part or skirt of the casting, because the metal being squeezed was not fluid enough to move up fully and uniformly into the skirt from the thick base. Too high a casting temperature caused excessive molten metal to extrude and be lost into spaces between the die and punch. Also, very large shrinkage holes developed in the thick base of the dome where the metal solidified last.

A correct temperature, in this case 2900° to 2950°F, allowed for good, full movement of the molten metal into the final configuration of the part with no porosity developed in any part of the casting (Fig. 11).

5.1.2 <u>Time, Accuracy, and Cleanliness of the Pour</u>

Pouring accuracy, length of pour time into the die, and cleanliness of the melt were found to be very important

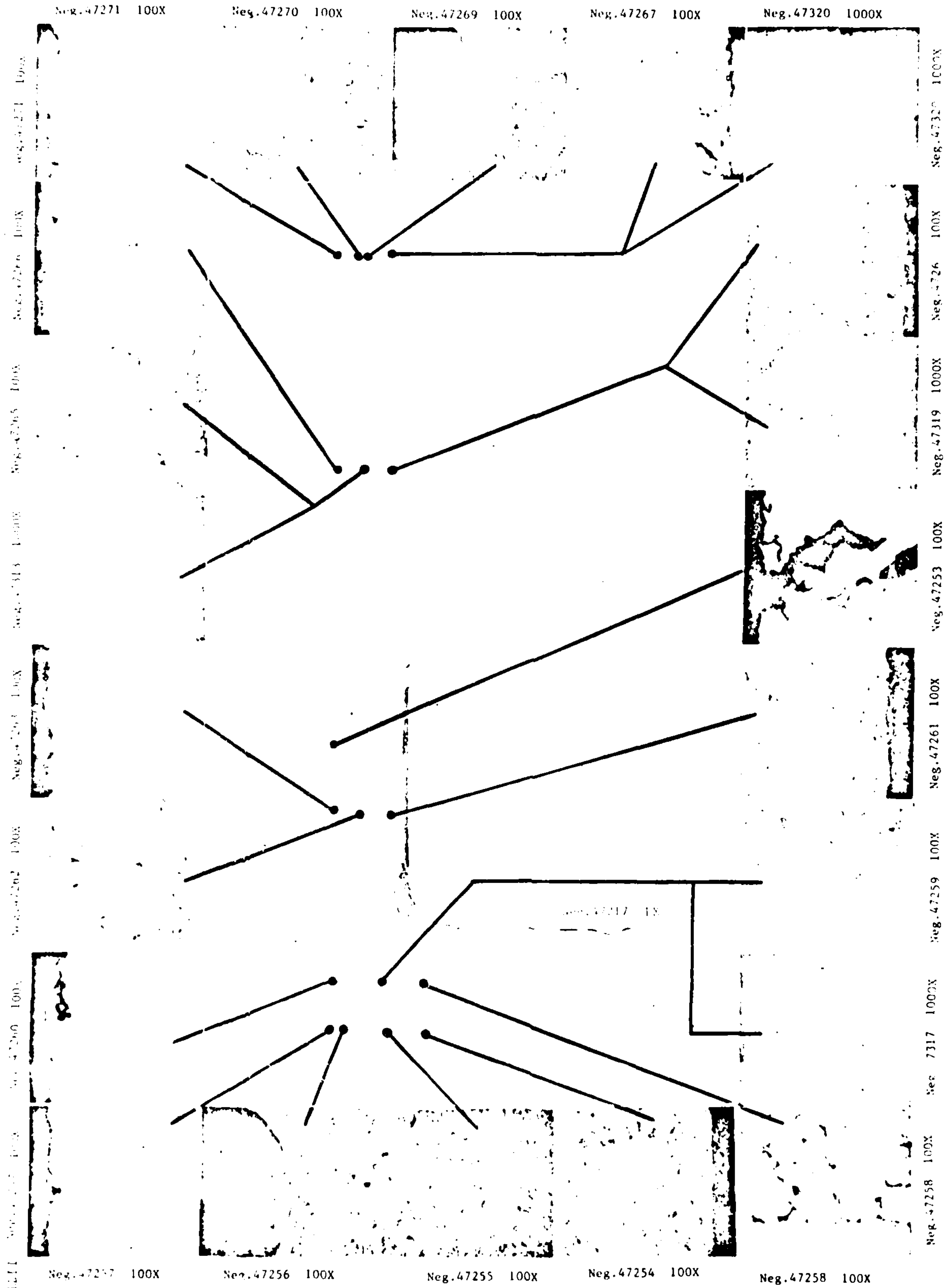


Figure 21

Photomicrographs, Taken at 100X and 1000X, of Samples from Preform Squeeze Casting No. 20. (Sample locations are shown above with respect to a macroetched section from the same casting.)

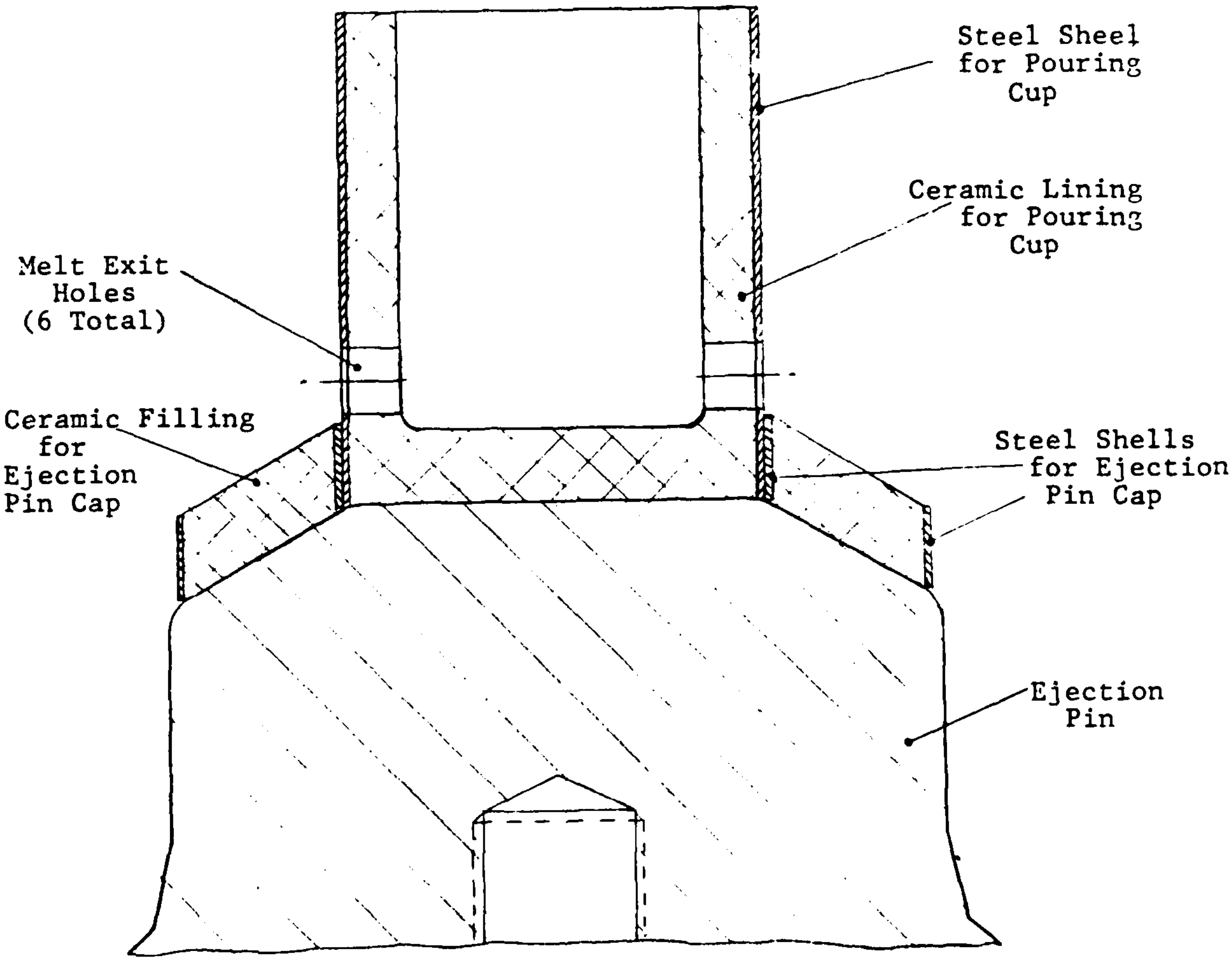


Figure 22

Pouring Cup Shown Positioned on Top of Ejection Pin for Squeeze Casting the Case Preform (Scale 1:2)

This cup was, at first, preheated to about 2000°F and placed on top of the ejection pin just prior to pouring. Since this procedure precluded very accurate alignment of the pouring cup, it was decided to cement the pouring cup exactly in place (at the start of the experiment) and then preheat it along with the rest of the tooling.

The pouring time was initially about 30 sec, and it took nearly 25 sec thereafter for the press to move down and forge the part. This resulted in partial solidification of the poured metal near the walls of the die and caused the "skin effect" illustrated in Fig. 23, whereby liquid metal flows up and around the already solidified crust or skin to form a discontinuity on the outside surface at the level to which the melt was originally poured. This is also shown in a sectioned and macroetched casting in Fig. 20b. However, in later experiments, the melt pouring time and the press descent time were reduced from 30 sec and 25 sec to 15 sec and 3 sec, respectively. A faster rate of pour was used, as well as rapid die closure via semiautomatic accumulator operation of the hydraulic press. The demarcation line observed earlier was virtually eliminated in this fashion.

Slag particles were skimmed off the melt surface both in the furnace and at the press just prior to pouring. The launder had a dam to restrict slag flow into the die cavity. To further restrict the amount of slag entering the die along with the melt, a sieve made from a refractory material "MACOR" was tried; but due to insufficient temperature of the sieve, metal flow was very sluggish and it ultimately froze. In future work preheating the sieve to the proper temperature and selecting the size of the openings in relation to the metal flow consistent with the shortest pour time desired will be investigated and optimized. In all of the cases, the slag was found to be present only on the outside surface of the preform below the original melt pour line. The depth of penetration of these particles is expected to be less than the depth of cut allowed for in finish machining the squeeze casting.

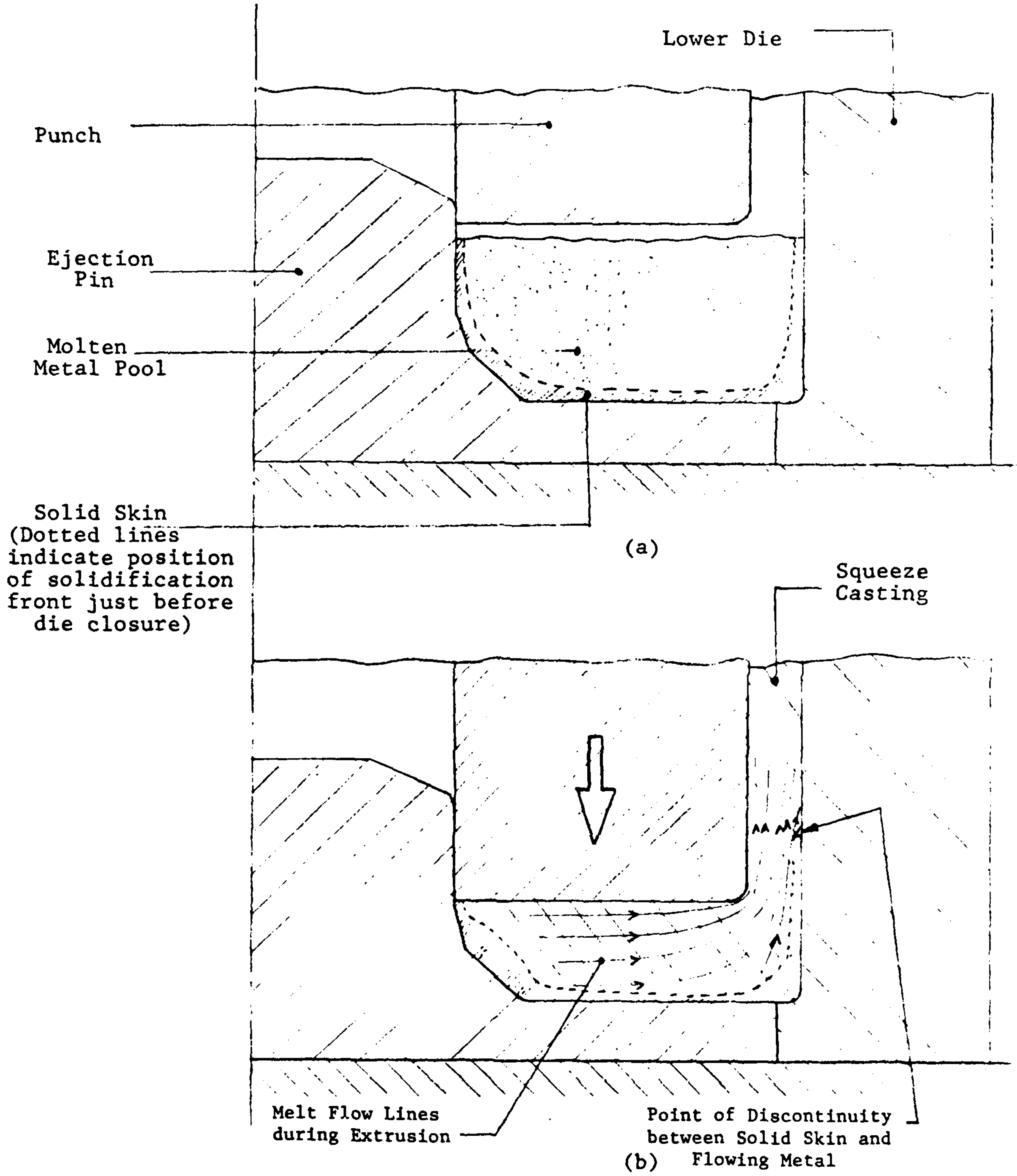


Figure 23

Illustration of Skin Effect in Preform Casting at Level of Original Melt Pool.
(a) Dies shown just prior to squeezing melt;
(b) dies shown in fully closed position.

5.2.3 Pressure Level and Duration

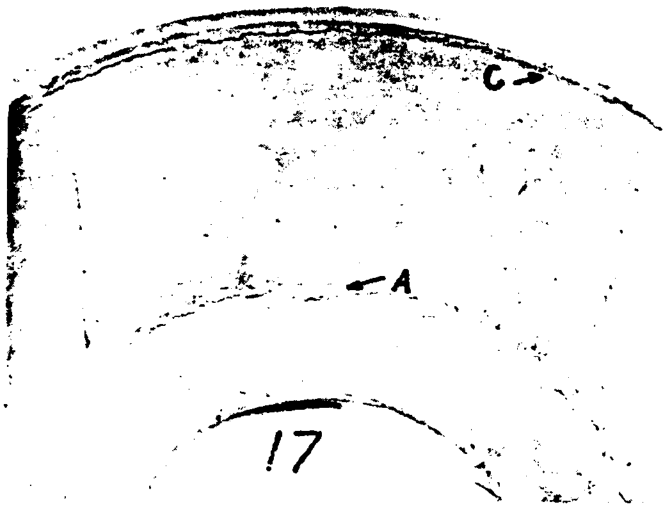
The press tonnage required for proper metal movement, die fill, and elimination of porosity was found to be in the range of 800-1000 tons. This corresponds to an applied pressure of 9900-12,400 psi.

The load had to be maintained for about 15-20 sec in order to avoid cracks, tears, and scale formation on the inside walls of the casting. This was noticed on castings made with 3-5 sec pressure hold time. When the ram retracts immediately after solidification is complete (about 3 sec), the preform casting is still very hot. This causes excessive scaling of the unprotected surfaces. Also, because of its low strength at the high temperature, the stresses developed when the punch pulls out of the casting cause the casting to crack and tear in overstressed regions. (This problem was not observed with the forward dome because its thin walls and higher cooling rate result in a lower casting temperature during punch retraction.) Figure 24 shows the improvement in inside surface quality obtained by increasing the pressure hold time from 0 to 20 sec.

5.2.4 Prevention of Welding Between Casting and Die

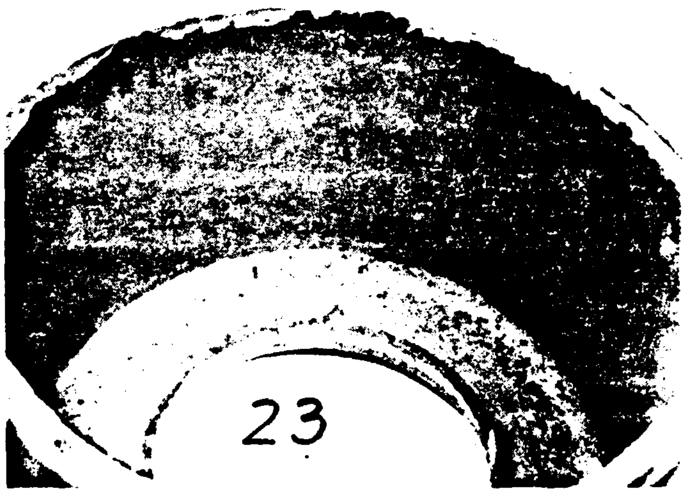
The occurrence of welding between the squeeze-cast preform and the lower die was not infrequent during the trial runs leading up to the "production run" wherein the deliverable items were made. This was largely due to the higher melt temperatures used at first and improper melt guidance which resulted in localized high-velocity melt streams that eroded the ceramic parting agent. However, once the melt temperature was lowered to a maximum of 2850°F and care was exercised in the fabrication and placement of the pouring cup, the problem of casting-to-die welding ceased to occur.

The process parameters were studied and optimized, as outlined above, and were used in the production of a series of squeeze castings, five of which were delivered to General Electric



Neg. No. 47090

(a)



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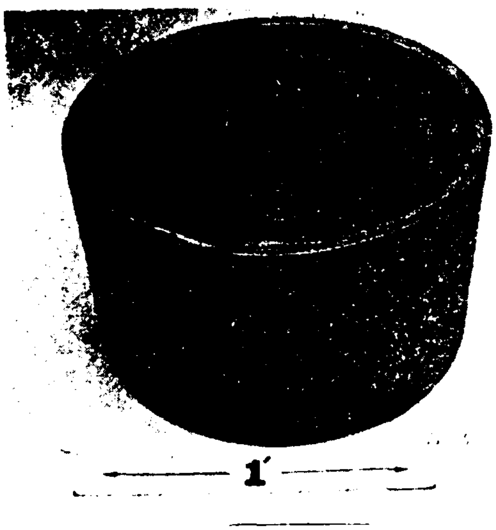
(b)

Figure 24

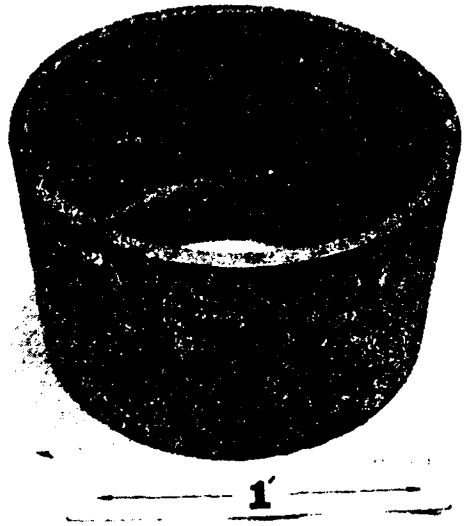
Inside Surface of Two Preform Castings Illustrating Improvement in Quality. (a) Preform squeeze casting No. 17; (b) preform squeeze casting No. 23.

Company for evaluation via spinning. While all five appear to be sound from a casting standpoint, their spinnability and the eventual applicability of squeeze casting to case preform manufacture will become known only after the G.E. spinning studies. Some of the production run preform squeeze castings are shown in Fig. 25.



Neg. No. 48328

(a)



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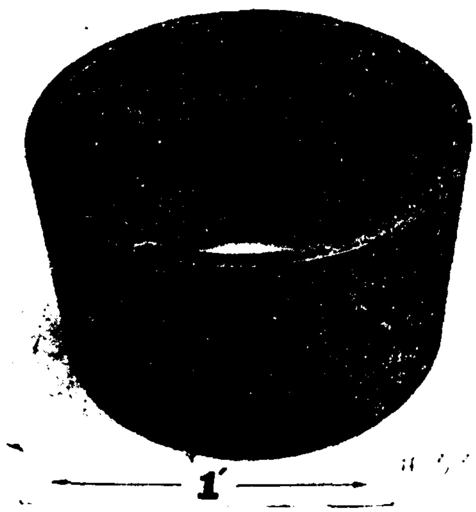

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(c)

Figure 25

Three of the Case Preform Squeeze Castings
Made as Deliverable Items

6. PRELIMINARY PROCESS SPECIFICATION

This specification is drawn up based on our experience so far in making forward domes and case preforms by squeeze casting as discussed in the previous sections. A number of recommendations stemming from past experience and most likely to be incorporated in the Phase II development work have been enumerated in Section 7 and may be incorporated in the production facility that might be set up for squeeze casting these parts.

6.1 Forward Dome

The component will be made by the squeeze casting process applying the usual standards of control over processing common in any good foundry. The work material will be melted in a large furnace and then may be transferred in a separate holding furnace in somewhat smaller quantities. From there the metal will be transferred into the squeeze casting die set in appropriate quantities. In the following specification, first the procedure is specified and then more details of the processing are given. Important conditions are presented in Table 2.

Procedure

- Open the dies and apply ceramic coating followed by graphite on all the die cavity surfaces and on the mating surfaces of the two die halves.
- Introduce the work material melt into the die.
- Close the dies, and build up and maintain the pressure for the desired duration.
- Release the pressure and open the dies as soon as possible.
- Remove the stripper plate if the die design used does not make it a part of opening the die itself.
- Move the ejection pin up to lift the squeeze casting from the bottom die.
- Lift the casting off the lower die, and retract the ejection pin to the lowest position.

- Inspect the die cavity; if any baremetal spots appear, coat them with a ceramic coating material. (Periodically, some die repair may also be needed, depending on the actual condition of the dies.)

Equipment

A hydraulic press will be used for the squeeze casting process. It should be capable of applying 1000 tons of load over sustained periods and up to 1500 tons for short durations. It should also have a minimum of 60 and 100 tons each for ejection of the casting and retraction of the top die, respectively. The press should have a programmable controller for proper and repetitive sequence of all the operations. The free speed should be at least 300 ipm.

Work Material

The material for squeeze casting should be selected to meet AMS 6431B for bars, forging, and tubing made from premium quality, consumable electrode vacuum melted stock, commercially designated as "Ladish D6AC."

Melt Temperature

The melt temperature in the melting and holding furnaces will depend on the melt transfer and handling facilities to be utilized. The temperature settings should be selected so that the melt temperature at the time of the introduction of the melt into the lower die is in the range of 2900° to 2950°F.

Die Temperature

The die temperature should be in the range of 450° to 500°F just prior to introduction of the molten work material into the dies.

Delay Time Prior to Application of Load

The time interval between the introduction of molten work material into the dies and the closing of the dies and application of pressure should be less than 10 sec. It can be controlled

Table 2

OPTIMIZED CONDITIONS FOR SQUEEZE CASTING THE FORWARD DOME

Melt weight	62-63 lb
Die temperature	450° to 500°F
Melt temperature when it is poured in die	2900° to 2950°F
Time from start of pour to application of load	10 sec (max.)
Press speed	Moderate (200-300 ipm)
Load cycle	1200-1500 tons for 5 sec

Note: Depending on the draft on the dies and the ejection mechanism, the casting may have to be cooled for a few seconds prior to ejection to minimize distortion during ejection.

by activating the ram movement on introducing the metal into the die and selecting proper free speed.

Mold Wash

Prior to starting a squeeze casting series, an alumina-based ceramic coating should be applied to all the die cavity surface but not on the mating surfaces of the two die halves. The ceramic coating should be replenished if bare metal becomes apparent in the die cavity. The mating surfaces of the dies should also be coated with a graphite-base forging lubricant that leaves a dry film.

Forging Load

The forging load should be approximately 1200-1500 tons for 5 sec for the forward dome and 1000 tons for 20 sec for the case preform. After releasing the load, the top die should be retracted as soon as possible. Then the stripper plate should be removed if the die design has not made it a part of retraction of the top die itself. The ejection pin should be moved up by the ejection system to lift the squeeze casting out of the bottom die. The casting can be removed from the dies manually or mechanically.

6.2 Case Preform

Similar guidelines regarding melt quality, transfer procedure, and casting process as outlined for forward dome shall apply to the case preform casting (see Table 3 for important conditions).

Table 3

OPTIMIZED CONDITIONS FOR SQUEEZE CASTING THE CASE PREFORM

Melt weight	160-162 lb
Die temperature	500°-550°F
Melt temperature when it is poured in die	2800°-2850°F
Time from start of pour to application of load	15-20 sec
Press speed	600 ipm or more
Load cycle	1000-1100 tons for 20 sec

Note: Depending on the draft on the dies and the ejection system, the casting may have to be cooled for a certain period of time prior to ejection to eliminate distortion.

7. PRINCIPAL RESULTS AND CONCLUDING REMARKS

7.1 Accomplishments and Main Results

In the course of this work for MIRADCOM, a number of accomplishments were attained which add significantly to the advancement of squeeze casting as a manufacturing technique. This is true particularly for large-sized steel components (50 to 200 lb).

IITRI work revealed that, although metallurgical parameters during processing were important, mechanical aspects of the process were equally so. Duration times of the metal flow into the die had to be minimal to prevent excessive skull thickness formation. Advance of the top punch onto the liquid metal had to be as rapid as possible, again to minimize solidification of the static liquid. Accuracy of the pour was very critical. Dead center pour was an absolute must, otherwise turbulence (nonuniform die fill) occurred creating defects in the casting. Also, this turbulence would erode and wash away the diffusion-inhibiting coatings applied on the die surfaces so that welding of the casting to the die wall would occur.

Cleanliness of the poured metal was also very important. Any dross from the melt surface poured along with the liquid metal was detrimental. Mechanical dams or bottom-pour setups are necessary to hold back the slag while casting. Otherwise, it plasters itself on the die wall and becomes an integral and degrading part of the casting. Surface skimming of forming oxide layers is advisable before applying pressure, particularly when there is a long pour time as for massive castings.

Metallurgically, it was found that the casting temperature of the melt had to be determined for the individual component. A spread of ±50°F was found acceptable, but the temperature did vary with the geometry and mass of the part. The 60 lb dome was cast at 2900°F, and 150 lb preform at 2850°F. Switching these temperatures resulted in imperfect squeeze castings. A few empirical studies are needed to determine the right temperature.

IITRI also found that the actual pressure used or the time at pressure was not necessarily as high or as long as cited in the Russian literature (the inventors and chief users of the process). A pressure of 10,000 psi (vs. 20,000 psi as cited) was adequate. Also, hold times as low as 5 sec (vs. 20 sec) worked out well. Some pressure duration, however, was required since zero time produced cracked parts. Lower pressure can mean longer die life and improved press performance. (Also, bigger parts can be made on the same press.) Lower hold times mean improved die life and increased productivity.

Almost everything learned in the course of this work moved in the direction of following a set of strict but not critical or sensitive rules. Once all the parameters are considered and finalized--usually with a noncritical spread for ease of production--the process works easily and simply to produce large-sized steel components of good quality on a repetitive basis.

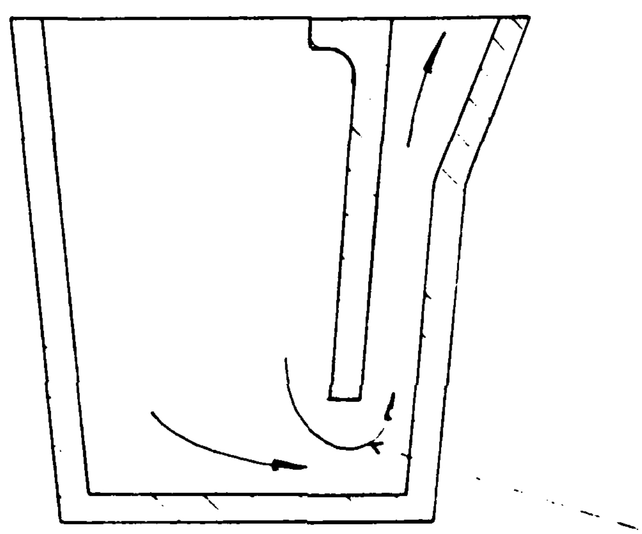
7.2 Comments on Proposed Pilot Production

To make further improvements in the quality of squeeze castings, through standardization of process parameters, equipment modifications, timing sequence automation, etc., a summary is presented here which can be taken up for evaluation during the second phase of the project. This would augment the chances of further improvement in the quality and bring down the per-unit cost in an actual production situation.

1. To clean the melt of the floating slag and to ensure that only clean steel enters the die, the following ideas are proposed:

   a. A graphite spoon shall be used to skim the slag off the melt in the induction furnace before it is poured in the transfer crucible.

   b. A bottom-pour type of transfer crucible shall be used (Fig. 26) to ensure that only clean metal is poured in the die and the slag is held back at the top.



Direction of
Melt Flow
During Pour

Figure 26

Schematic Illustration of Bottom-Pour
Crucible for Reducing Slag Transfer

c. To further ensure entry of clean metal into the die, a refractory sieve shall be located in the exit path of the launder and preheated to a sufficiently high temperature to avoid freezing of the melt. This should act as the final barrier to any slag particles that might still be present on the melt surface.

2. It is proposed to move the 150-lb induction furnace closer to the press to reduce the time it takes at present to bring the molten metal to the press. This would result in:

   a. Less oxidation at the melt surface due to shorter exposure time to the atmosphere.

   b. Less oxidation due to lower pour temperature from the furnace to transfer crucible which must be kept higher at present so as to maintain the proper pour temperature in the die.

3. To obtain optimum pouring conditions and avoid turbulence, the geometry and dimensions of the launder will be standardized with a pattern. The dam to hold back the top oxidized layer on molten metal shall still be used.

4. A precisely measured weight of molten metal shall be transferred into the transfer crucible with the help of suitable weighing arrangements.

5. The timing sequence of the press shall be automated as much as possible to obtain uniformity and repeatability in the cast parts.

6. A suitable method for fast ejection of casting, e.g., air blast quench, shall be investigated to get a faster casting ejection, particularly for the preform.

7. The top die (punch) shall be water-cooled for faster and easier stripping of the forward dome casting.

8. The dies will be suitably reconditioned between each casting, using mechanized

wire brushes and air-blast cleaning to get better surface.

9. To minimize columnar grain growth and possible reaction with die, the molten metal will be cast as rapidly as possible with pressure applied at start of melt solidification.

10. In order to improve casting surface, new parting agents to be applied to the die surfaces shall be investigated. This will include the elimination of Al_2O_3 sprays and the possible deposition of plasma arc bond-inhibiting materials giving better surface.

11. Flushing of the melt during transfer, till it is poured into the die, with a protective gas will be carried out to minimize contamination.

7.3 Preliminary Cost Analysis and Comparison of Forging, Sand Casting, and Squeeze Casting Processes for Missile Parts

In order to demonstrate the savings in production cost that can be realized by squeeze casting the forward dome and case preform missile parts instead of forging them, a preliminary cost analysis was made of the forward dome component which is presently manufactured by machining from a forged block of D6AC steel. A comparative estimate was also made of the sand casting process, whose costs fall in between those of squeeze casting (low) and forging (high) without, however, approaching the properties and product qualities of either.

The cost analysis was based on the pricing method described in the appended article, "Pricing by Formula" by S. Storchheim. This technique has been found to give quick, accurate cost results for a variety of manufacturing processes where the rate of production is reasonably high.

The prices are based on the cost of direct labor, manufacturing overhead at 350% of direct labor, and material costs plus 55% of the sum of the above three for G & A costs, sales commissions or salaries, distribution costs, and profit.

The rate of production (N) was estimated as 5/hr in the case of forging, 12/hr for squeeze casting, and 5/hr for sand casting. At these rates of production, the size of the labor force is estimated to be 3 men for forging plus 7 men for machining, 3 men for squeeze casting plus 3 men for finish machining, and 3 1/4 men for sand casting plus 4 men for machining.

The wage rate was taken at $5/hr, and the cost of raw material as 36¢/lb. The material usage would be 343 lb, 60 lb, and 120 lb for forging, squeeze casting, and sand casting, respectively.

The sales price, under the above assumptions, for each process is thus:

$300/part - forging

$230/part - sand casting

$160/part - squeeze casting

For the forward dome component, a cost savings of nearly 50% can be expected by using squeeze casting as the preferred manufacturing method. Similar conclusions can be drawn for the case preform missile component.

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APPENDIX

PRICING BY FORMULA—
a guide to *your* costs and your *competitors'*

SAMUEL STORCHHEIM, Vice President and Technical Director
Sinteral Corp., Jamaica, New York

• The average man in product design or manufacturing, and even professionals with strong academic backgrounds and considerable practical experience, have little or no knowledge of how to quickly and reliably determine the sales price of the products their companies or their competitors manufacture. Yet when you take a closer look at the situation, it turns out that costing procedures are not the mystery many people in-the-know pretend they are. Not only can costing procedures be rather simple and straightforward, but it's possible to use shortcuts which make it possible to calculate prices with great rapidity and a minimum of effort.

In setting up a manufacturing plant for a newly perfected aluminum powder metallurgy (AL P/M) process, we at Sinteral Corp. found a strong need for a system that would give us good "rules of thumb."

The AL P/M process, for the first time, allows for the fabricating of both porous and highly densified parts, of pure aluminum or alloyed. It is capable of remarkably high production rates up to 500,000 pieces per hour, very close (.0003 in.) tolerance control, eliminates most secondary machining operations, and produces substantial cost savings.

In addition to the problem of pricing, other problems that had to be solved at the outset included volumes to be produced per hour, size of parts to be considered, type of equipment to be used, capital required for the production line, type of personnel to hire, cost of materials to be used, and what type of supervisory and administrative personnel should be used to staff the corporation.

In our case, consulting the existing literature was of little avail, and talks with various professionals and accountants added but little more to the picture. It, therefore, was necessary to develop our own pricing method. The method we devised is simple, fast, and accurate. In addition to its usefulness in pricing our own products, we find that it enables us to cost a competitor's products with reasonable accuracy, regardless of manufacturing methods or materials used. This has given us an additional tool with which to gage the production rate necessary to be competitive with other manufacturers.

Perhaps the most unusual aspect of our findings is that our new AL P/M process had the ability to produce parts in almost any hourly quantity. We, thus, are dealing with a variable that in most part-producing methods is fairly well fixed, or can be varied only through a limited range. It became our controlled variable, which we use in our costing curve plots.

We are set up currently with 200-, 100-, and 25-ton mechanical compacting presses, a 10-ton rotary press, two production belt sintering furnaces, secondary finishing equipment, and testing facilities. This equipment gives us the capability to produce parts of up to 30-50 sq in.

Basic Preliminary Considerations

To understand our pricing method, it must be accepted that the sales price of any item is based on the following three factors:

1. The cost of the direct labor;

2. The manufacturing overhead or burden, consisting of those indirect costs which contribute to the running of a factory but cannot be directly assigned to the product. For convenience, the overhead cost is quickly figured as a percentage of direct labor. The percentage varies greatly for different companies, in some cases being as low as 100 per cent and in others as high as 1000 per cent or more. Usually, 250 to 350 per cent is taken for a full-sized manufacturing operation of mass production parts. The figure used should always be verified from plant operating statistics;

3. Material costs when they can be directly allocated to the product. These, too, can vary substantially, and an actual determination of the figure is preferred over an arbitrary percentage related to direct labor.

When items 1, 2, and 3 are added together, the manufacturing cost of the product is obtained.

To the cost figure thus obtained must be added the general and administrative (G&A) costs for running the company, sales commissions or salaries, product distribution costs, and, finally and most importantly, the profit. Usually, these costs total anywhere from 35 to 70 per cent of manufacturing costs, with the actual value varying, of course, with different types of organizations.

A company with few administrators, limited promotional costs, and a single type of mass-produced product might, for example, use the 35 per cent figure. A corporation which is more diversified and employs more administrators, might use the higher figure of 70 per cent. Usually, a typical medium-sized corporation will find these expenses to be about 55 per cent. Of this total, G&A is normally taken at 10 per cent of the product's market value, distribution at 15 per cent, and profit at 15 per cent.

Deriving the Formula

Calculating the various figures can be time consuming—and, frankly, quite boring. But there is a relatively simple way out. It involves taking the known factors and deriving a single manageable formula from them, as follows:

$$
\begin{aligned}
TC &= DL + OH + M + .55\,(DL + OH + M) \\
&= DL + 3.5DL + M + .55\,(DL + 3.5DL + M) \\
&= 6.98DL + 1.55M \\
&= 6.98DL + (1.55)\,(.002245NCw)
\end{aligned}
$$

or

$$TC = 6.98DL + .00349NCw$$

or

$$
\begin{aligned}
SP &= \frac{TC}{N} \\
&= 6.98\frac{DL}{N} + .00349Cw
\end{aligned}
$$

Legend

SP = Sales price in dollars per piece

TC = Total price in dollars for one hour's production

DL = Direct labor in dollars per hour

OH = 350% DL

M = Materials cost based upon:

$M = (w)\,(N)\,(C)\,(1.02)\,(2.2/1000)$

where:

w = weight in grams

N = number of pieces per hour

C = raw material cost in dollars per pound

1.02 = 2% scrap loss for the process

$\frac{2.2}{1000}$ = conversion factor for grams to pounds

or

$M = 0.002245NCw$

It should be appreciated that this formula is more-or-less an average one, and as such it may not be applicable to every manufacturer's products. But it can be adjusted by obtaining the proper values from a company's accounting department and factory superintendent.

Application of the Formula

In our case, the objects in the price determination were two-fold. One, of course, was to obtain the sales price. The second was to see what production method should be used and what the optimum production rate should be.

The part chosen for the test was a small cylinder required in large quantities. Large volume allowed us to use either a large single station (capacity up to 1000 per hour) compacting press, or small rotary presses (capacity up to 40,000 per hour) for compacting the aluminum powder into green compacts.

These high density compacts (95 per cent of theoretical density) then are dipped in graphite slurry and passed through a continuous belt furnace in bulk to sinter them into metallurgically acceptable parts. The graphite slurry, which prevents the parts from sinter-welding or sticking together during sintering, are pickled off in a continuous bath setup after the parts came from the furnace.

With the parameters set, N was varied from 400 to 40,000 pieces per hour, because this entire production range could be powder weighed, mixed with pressing and alloying additives, and green pressed by one man. The furnace operator could control the slurry dip, sinter, pickle, and subsequent drying operations. To avoid complicating the analysis, no additional processing was considered, except for quality control and packaging for shipment.

Statistical inspection was calculated to be going on during the entire process, with the dried pieces being bulk-packaged for shipment. In the case of 400 pieces per hour, it was considered that a fourth of a man would be needed, while at 40,000 per hour 2½ men would be needed. Thus, for 400 pieces per hour a total of 2¼ men would be needed, and at the 40,000 per hour rate, 4¼ men would be used.

A direct labor figure of \$3 per hour per man is generally accepted as being an average figure. However, this, too, was varied to show the effect if the number of men required for production could be reduced by up to one-half.

To show the effect of weight, the sample was costed at two different weights: 1 gram and 10 grams per piece, respectively. It should be remembered that these figures are considered to include all processing losses such as spillage, rejects, machining losses, etc.

To illustrate the effect of the key variables such as direct labor (DL), production rate (N), raw material costs (C), and weight (W), four different costing curves were constructed. Using 350 per cent overhead (OH) and G&A etc. expenses at 55 per cent of the manufacturing cost, Fig. 1 was developed to show the relationship between sales price and production rate for pieces of different weights (1 and 10 grams, respectively). It was computed

effects of production rate, material, direct/indirect labor

FIGURE 1

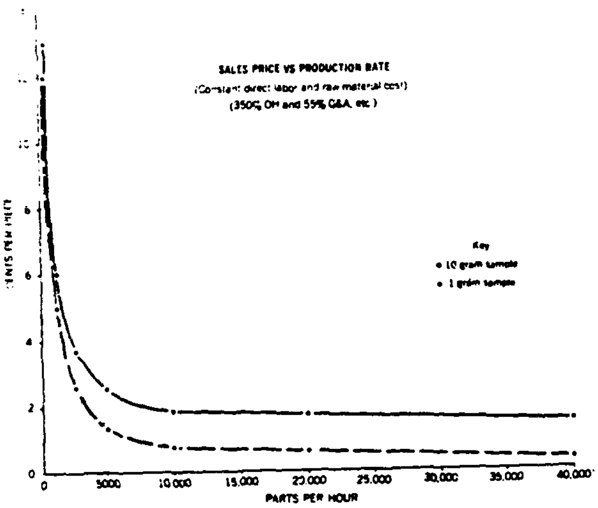


FIGURE 2

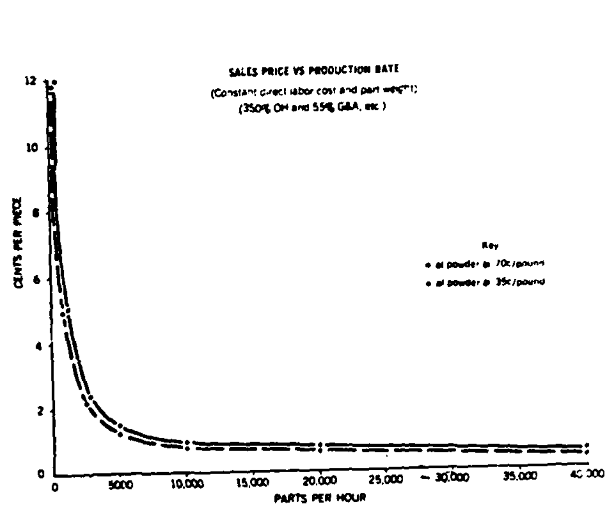


FIGURE 3

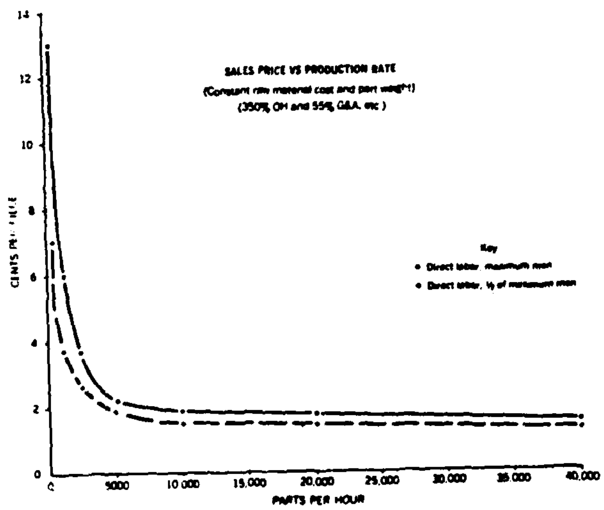
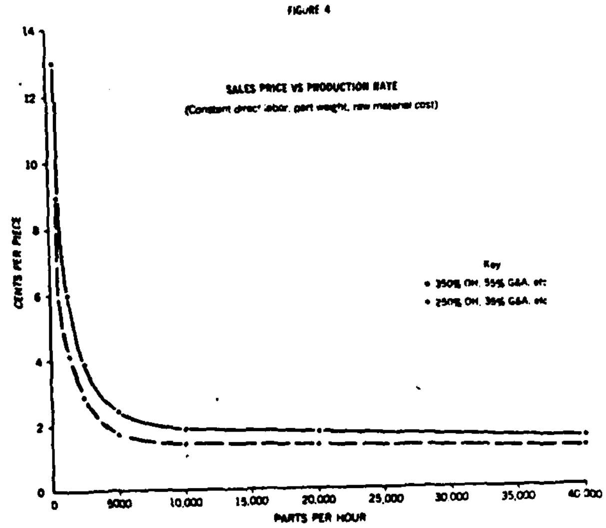


FIGURE 4



with a DL figure of \$3 per hour per man, and a raw material cost of \$0.35 per pound.

Fig. 2 shows sales price versus production rate for variable raw material costs of \$0.35 and \$0.70 per pound with DL kept constant at \$3 per hour per man and weight at 10 grams.

Fig. 3 shows sales price versus production rate when the direct labor costs are varied from \$3 to \$1.50 (half as many men) and raw material at \$0.35 per pound and weight at 10 grams per piece are kept constant.

Fig. 4 compares the sales price generated by using two OH rates (350 vs 250 per cent) and two G&A etc. rates (55 vs 35 per cent), with all other variables being held constant except the number of pieces produced per hour. These include DL at \$3 per hour per man, weight at 10 grams per piece, and material at \$0.35 per pound. In this case the sales price formula for 250 per cent OH and 35 per cent G&A etc. rates is as follows:

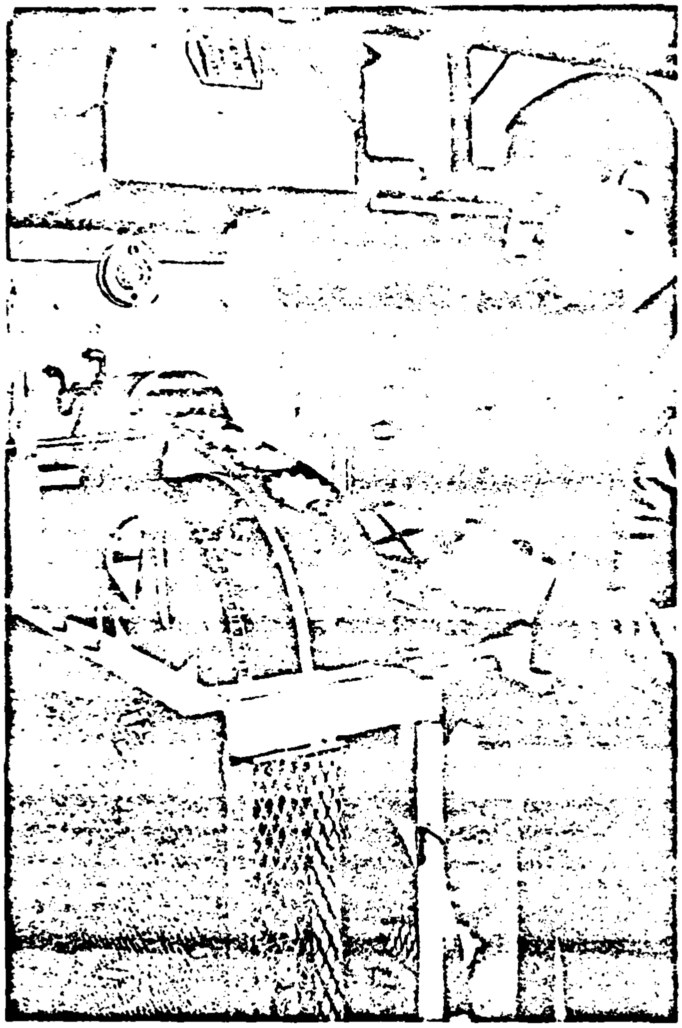
$$TC = 4.73DL + .0030\ NCw$$

or

$$SP = 4.73\ \frac{DL}{N} + .0030\ Cw$$

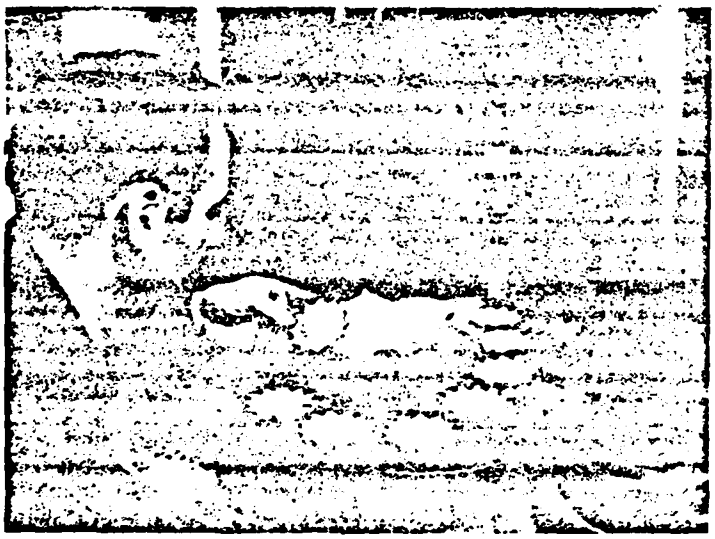
Comparison Results

All four sets of curves have one basic characteristic in common—at low production rates, the sales price per



tools for optimization

Representative operations performed at Sinteral include (above) rotary pressing of aluminum alloy slugs, (below) green pressing in a single-cavity die of decorative chandelier parts, and (left) the sintering of the decorative powder metal part



# of costs--they're available for your use

part is high. As shown, the prices drop exponentially with higher production rates, knee, and then asymptotically approach a minimum pricing figure regardless of how fast the parts are made.

It becomes apparent that one should try at all times to work just to the right of the knee of the curve. The exact position past this point will be governed by how much capital one wishes to invest to attain higher speeds, how many additional people can be put on the line (training time must be considered), the extra work area needed, the size of the total order, warehousing considerations, and the investment in manpower and equipment needed for secondary machining operations.

As may be seen in Fig. 1, a change of ten times in weight creates a significant price change. Of course, in looking for economy one cannot expect to decrease a part's weight by 90 per cent as a general rule; but for relatively large parts used in great quantities, there is always the possibility of creating a significantly lowered price by designing thinner sections or introducing weight-saving recesses. For example, with a part weighing 55 grams, a 10 per cent weight reduction is not unreasonable to attain, and for each-million part quantity, this would amount to a $7000 savings.

It is interesting to observe where the knee of the curve indicates the production rate to be used. For lighter pieces, the rate moves to greater values, and shows that the 1-gram part can best be run at 10,000 pieces per hour while the 10-gram part is best run at 5000 pieces per hour. This means that one is not a captive of excessively high production rates for larger parts, but can conveniently go to slower and more powerful rotary presses.

As shown in Fig. 2, doubling of raw material cost, interestingly, does not have too great an effect on the overall price for the part weighing 10 grams. However, for a part weighing 100 grams, the effect of doubling the price of raw material is quite significant. For example, at 10,000 pieces per hour at $0.35 per pound, the cost is $0.0175 per piece; while at $0.70 per pound, cost rises to $0.0287 per piece.

Reduction of direct labor to one-half its original value shows a marked cost savings up to the knee of the curve in Fig. 3, but past the knee it is not of extreme importance. This means that if the proper production rate is chosen, more people can be employed or better wages paid for more highly skilled personnel. Mistakes in the production cycle can be more readily tolerated, as they do not assume critical proportions, and better quality control and product integrity can be obtained.

As shown in Fig. 4, the observations made above (Fig. 3) as to the effect of direct labor hold true if OH and G&A etc. rates are reduced. The proper choice of production rate means that more or better supervisors and administrators can be afforded. Such expenses as pension funds, institutional advertising, and R&D commitments that could not be considered in a marginal operation now are possible.

Checking the Competition

There are many times when a company would like to know a competitor's sales price, as a yardstick against which to gage its own pricing structure. With a reasonably good concept of how the competitive part is manufactured, it is possible to use the general formula for this purpose. To illustrate, we had to compete against a zinc die cast wall plaque used for housing common electric light switches. The plaque was highly ornate and brass plated. Because of its decorative design, accurate calculation of weight from a print would have been difficult, so we weighed it and found it to be 80 grams. We then converted that weight to an equivalent weight in our aluminum powder metallurgy alloy as follows: The density of our component (2.74 grams per cc) divided by the density of the zinc cast alloy (6.6 grams per cc), multiplied by the zinc cast weight (80 grams). The weight of our aluminum powder part was determined to be 33.2 grams.

To calculate the cost of the die cast wall plaque, it was estimated that one man using a multiple cavity die was capable of die casting at a rate of 970 pieces per hour. This high rate was determined on the basis that the part was quite thin in cross section and the number of cycles per hour was therefore high. The additional steps of trimming and buffing the gate areas were estimated to take ½ man, while inspection and packaging would take another ½ man. Thus, two men, in total, would be utilized at $3 per hour per man. Setting the formula to work, and using a price of $0.165 per pound for the aluminum alloy, the following was determined:

$$
\begin{aligned}
TC &= (6.98)\,(2)\,(3.00) + (.00349)\,(970)\,(.165)\,(80) \\
&= 41.80 + 44.80 \\
&= \$86.60 \\
SP &= \$86.60/970 \text{ pieces} \\
&= 8.9¢ \text{ per piece}
\end{aligned}
$$

With the estimated price of 8.9¢ per die cast piece, we designed our production rate for the aluminum powder metallurgy process so that a sales price of 8¢ per piece was quoted. The users later told us that the price of the zinc die cast part was 9¢ per piece. ■

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